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THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

AUTOREGRESSIVE MODELING OF THE LOWER STRATOSPHERIC WINDS AND TEMPERATURE FOR AN EQUATORIAL LOCATION

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

MASTER OF SCIENCE IN METEOROLOGY

By

KIRK EDEL LEHNEIS

Norman, Oklahoma

1980

80-3'T

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AUTOREGRESSIVE MODELING OF THE LOWER

STRATOSPHERIC WINDS AND TEMPERATURE

FOR AN EQUATORIAL LOCATION

A THESIS

APPROVED FOR THE SCHOOL OF METEOROLOGY

By

Claude E. Duchon

James F. Kimpel

Amos Eddy

ACKNOWLEDGEMENTS

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The data for this study was obtained through the United States Air Force Environmental Technical Applications Center at Scott Air Force Base, Illinois. The help of all the staff is greatly appreciated. Finally, thanks goes to the United States Air Force for assigning me to the Air Force Institute of Technology and allowing me to come to the University of Oklahoma to conduct this research.

ABSTRACT

The purpose of this research was to forecast monthly mean values of zonal and meridional wind components and temperature for 11 pressure levels from 100 to 10 mb for an equatorial location. Rawinsonde data for Kwajalein ($8^{\circ}43'$N, $167^{\circ}44'$E) were used to compile 33 data series of monthly means for the three variables and the 11 pressure levels. Univariate autoregressive (AR) and multivariate autoregressive (MVAR) models were used to forecast monthly means of each variable at each pressure level for a 12-month period. In order to get a quantitative measure of the effectiveness of the AR and MVAR forecasts, root-mean-square-errors (RMSEs) were calculated and compared with RMSEs computed for climatology "forecasts".

AR and MVAR forecasts were found to be about as good as or better than the climatological (as defined in this thesis) forecasts for a period of six to 12 months. AR and MVAR forecasts of the zonal wind component were substantially better than the climatological forecasts. In some cases, RMSEs for the AR and MVAR models were over 50 percent less than the climatology RMSEs. Very little difference was found between AR and MVAR forecasts and

climatological forecasts of the meridional wind component. For temperature forecasts, climatology tended to do slightly better than either the AR or MVAR forecasts, although the differences were usually about 0.5°C or less.

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CHAPTER I

INTRODUCTION

In 1883 after the eruption of Krakatoa in the East Indies, the dust that spewed forth from the volcano was observed to travel above 25 km from east to west at 33 ms^{-1}, circuiting the world in the equatorial region at least twice. Van Berson's studies in Central Africa in 1908 and Van Bemellen's studies in Batavia in 1909 found westerlies above 20 km in the low latitudes where easterlies were thought to occur (Belmont and Dartt, 1964). Until the late 1950's, it was believed that the Berson westerlies and the Krakatoa easterlies existed simultaneously as two opposing flow patterns (Wallace, 1973).

With the beginning of more regular rawinsonde observations, McCreary (Wallace, 1973) found that westerlies did not appear at the same level from year to year, but were replaced sometimes by easterlies. Working independently, Reed (1965) and Veryard and Ebdon (1961) announced the discovery of a quasi-biennial or 26-month oscillation (QBO) in the lower tropical stratospheric monthly mean zonal winds. As used here, the tropical stratophere is defined as the region within about 20^{o} of the equator and extending from the tropopause around 17 km to the stratopause near 50 km. The lower stratosphere is that part of the stratosphere extending from about 17 to 35 km and the upper stratosphere from 35 to 50 km.

1.1 Zonal Wind

Investigations have shown that most of the variance about the mean zonal wind in the tropical stratosphere can be explained by the sum of the annual and semi-annual cycles and the QBO (Wallace,1973). Amplitudes of these cycles are summarized in Figure 1 for approximately 9^{o}N latitude (Reed, 1965; Webb, 1966; Groves, 1973; Belmont et al, 1974; Holton, 1975).

1.1.1 Annual and Semi-Annual Cycles

Throughout the tropical stratosphere, the amplitude of the annual cycle is on the order of 10 to 30 ms^{-1} with two exceptions. It diminishes to less than 10 ms^{-1} between the equator and 10^{o}N latitude and also below about 30 km south of the equator (Belmont et al, 1974). The annual cycle is in response to seasonal changes in the incoming solar energy in the ozone layer (Wallace, 1973).

The semi-annual oscillation of the zonal wind component reaches a maximum amplitude of about 25 ms^{-1} near the stratopause at about 9^{o}N latitude. Meyer (1970) disclaimed the theory advanced by Webb (1966) that the semi-annual cycle is related to the semi-annual cycle in insolation in the equatorial region. Meyer felt that a semi-annual periodicity in momentum flux is needed to explain the semi-annual cycle. The momentum source is not presently known but he suggested the meridional fluxes produced by the diurnal and semi-diurnal tides may be responsible.

1.1.2 Quasi-Biennial Oscillation

Reed (1965) found that the amplitude of the quasi-biennial oscillation is largest over the equator (about 20 ms^{-1} near 30 mb), progresses downward at about 1 km per month, extends upward to at least 30 km and deteriorates as it approaches the tropopause. He observed the period of the oscillation to be irregular, varying from 21-30 months. Groves (1973) determined the period to vary from 20-36 months and Nastrom and Belmont (1975) used 29 months in their study.

Since the early works of Reed, research related to the QBO has been mainly in three areas: a search for the QBO at middle and higher latitudes, in other parameters, and at higher altitudes; a search for a theory to explain its being; and a deeper understanding of the two waves, Kelvin and mixed Rossby-gravity waves, that apparently cause the QBO phenomenon. The QBO has indeed been found in middle and higher latitudes (Angell and Korshover, 1962; Nastrom and Belmont, 1975); in other parameters: surface temperature, precipitation, pressure, lake levels, varves and perhaps tree rings (Landsberg et al, 1963); and at higher altitudes (Groves, 1973).

Most of the early theories of the QBO centered around thermal forcing by some cycle in solar output (Shapiro and Ward, 1962; Staley, 1963; Probert-Jones, 1964; Westcott, 1964). These theories require enormous variations in solar output to drive the QBO (Wallace, 1973).

To date the most accepted theory is that developed by Holton and Lindzen (1972) in which eastward propagating Kelvin waves and westward propagating mixed Rossby-gravity waves impart westward and eastward momentum, respectively. upward into the mean zonal stratospheric flow. If the westerly momentum carried by these waves is absorbed in westerly shear zones and the easterly momentum is absorbed in easterly shear zones, then the shear zones will propagate downward, as is observed.

Wallace and Kousky (1968), Kousky and Wallace (1971), Lindzen (1971), Kousky and Koermer (1974), Miller et al (1976) and Plumb (1977) are some who have contributed to the knowledge of the existence of Kelvin and mixed Rossby-gravity waves and their link with the QBO. Kelvin and mixed Rossby-gravity waves both propagate zonally and vertically, with periods of 10-15 days and 4-5 days, respectively. Kelvin waves propagate eastward at about 30 ms^{-1}, while mixed Rossby-gravity waves propagate westward at about 20 ms^{-1}. Both waves, as mentioned before, propagate upward, which suggests a tropospheric origin (Wallace, 1973).

Recently Brier (1978) advanced a new theory indicating that the QBO may be a result of the annual forcing by solar heating. He presented evidence suggesting the QBO may be produced through a negative feedback process involving the annual cycle and interactions involving the atmosphere-ocean-earth system.

1.2 Meridional Wind

Many researchers (Murgatroyd and Singleton, 1961; Murgatroyd, 1969; Angell, 1974; Wallace and Tadd, 1974) have studied the meridional wind component of the tropical lower stratosphere. They found that the magnitude of the meridional wind varied from near zero to on the order of 1 ms^{-1}.

1.3 Temperature

In 1961, Veryard and Ebdon (1961) announced their discovery of the existence of a QBO in stratospheric temperatures near the equator. Amplitudes were found to be on the order of 2^{o}C in the middle and upper parts of the lower stratosphere. At 20 and 30 mb the peak in the temperature oscillation preceded that in the wind oscillation by about 6 months. Because of the more rapid downward progression of the wind oscillation, the temperature and wind oscillations came into phase around 80 mb. Nastrom and Belmont (1975) found the QBO to have a maximum amplitude in the tropics of about 2^{o}C near 30 km. Figure 1 displays the amplitudes of the QBO, annual and semi-annual cycles for 9^{o}N latitude which Nastrom and Belmont (1975) found. The annual temperature wave in the tropical stratosphere was found to be almost uniform, having an amplitude of about 2°C throughout. A maximum amplitude of about 3°C for the semi-annual wave in the tropics was found near 40 km.

1.4 Purpose of the Study

The present study is concerned with a portion of the lower stratosphere from 17 to 31 km corresponding to 100 to 10 mb and uses data from 1963-1973 for Kwajalein (8°43'N, 167°44'E) in the Marshall Islands of the Western Pacific Ocean. This research is an outgrowth of a desire to study the atmospheric variation and prediction of monthly mean values of temperature and zonal and meridional wind components for specific altitudes along a re-entry path for missiles. Furthermore, Brier (1978) stated that a number of investigators indicated the equatorial QBO plays a part in determining the tropospheric circulation in middle and high latitudes and that the QBO may have some predictability value for various surface parameters a season or more in advance.

1.5 Three Approaches

In order to forecast monthly mean values of temperature and wind, three approaches can be taken: climatological, deterministic and stochastic. The climatological approach is a "null" forecast as it is nothing more than a recurring series of 12 monthly means, where a particular monthly mean is based on a specified number of years of data. In a deterministic approach, the variable is known exactly for all time and hence is a mathematical idealization. Unfortunately, this method cannot be used in this study because all the physical processes involved are not completely understood. We, therefore, will use a stochastic approach, which takes into account the uncertainty of the process and describes the given time series of a variable as a random variable with an associated probability density function. A given time series can be represented by an autoregressive model which represents the process as a linear function of its past (Jones, 1964). Autoregressive models take into account the auto-correlations and multivariate autoregressive (MVAR) models in addition take into account the cross-correlations between two or more time series. In both models the series are projected forward in an objective way.

1.6 Outline of the Study

In using autoregressive models, one approach would be to subtract out the annual and semi-annual cycles and let the remainder including the QBO, which is quasi-periodic since its period varies from 21 to possibly 36 months, be the random part. A second approach would be to assume that the entire series is random. In order to limit the number of computations and to facilitate data manipulation, the second approach was chosen. Akaike's FPE criterion (Akaike, 1971) which permits one to use the model with the minimum mean square one-step prediction error was utilized to objectively select the order of the autoregressive process.

In the next chapter, the data set and the method used in computing the monthly means are discussed. In chapter III the results of a Fourier Analysis of the monthly means of the wind components and temperature are given, followed by descriptions of the univariate and multivariate autoregressive models. Chapter IV provides an analysis of the forecasts of monthly means of the wind and temperature using the univariate and multivariate autoregressive models. Finally, chapter V contains a summary of the results, conclusions, and several recommendations for future research.

CHAPTER II

PREPARATION OF MONTHLY DATA

2.1 The Raw Data Set

Rawinsonde observations were obtained through the USAF Environmental Technical Applications Center (USAFETAC) for Kwajalein, in the Marshall Islands of the Western Pacific. A total of 15,918 individual rawinsonde runs, dating from May 1952 to December 1973, were available. Only temperature, wind direction and wind speed for 100, 80,70, 60, 50, 40, 30, 25, 20, 15 and 10 mb levels were utilized in this study. Temperature was given in degrees Celsius to the nearest tenth, wind direction was reported to the nearest whole degree and wind speed to the nearest ms^{-1}.

Up to mid-1957, temperature and wind values in the data set were given for each of the above levels except at the 70 and 25 mb levels. Temperature values provided by USAFETAC at 70 and 25 mb were a linear interpolation from the two adjacent levels. Wind direction and speed were not provided by USAFETAC. Data were generally for zero to four times daily at 03, 09, 15 and 21 GMT. After 1 July 1957, temperature and wind values at the 25 mb level were recorded from the observations. Beginning in June 1957, release times were changed to 00, 06, 12 and 18 GMT. The temperature data at 70 mb continued to be an interpolated value between the two adjacent levels. Finally, beginning 1 January 1961, temperature and wind data for the 70 millibar level were recorded from the reported observations. Hence, 11 levels of temperature and wind direction and speed were being recorded from 100 to 10 mb, zero to four times daily, usually at 00, 06,12 and 18 GMT.

An analysis of the entire data set showed that the number of observations per month for 100 mb varied from 0 to 129 for temperature and 0 to 124 for winds. At 10 mb, the number of observations varied from 0 to 66 for the winds and 0 to 72 for temperature. Obviously, data were not available the same number of times each day for each level, probably due to balloon bursts before reaching a particular millibar level, loss of balloon track due to high winds and low angle, malfunction in equipment or possibly nonavailability of balloons due to lack of funds. The large variation in the number of observations per month for each millibar level raises the question of non-homogeneous data. This question is addressed in section 2.3 which discusses the final set of data used in the study.

2.2 Computation of Monthly Means

Since this study deals with monthly mean values of temperature and zonal and meridional wind components and because of the variability in the number of observations per month and the time of the day they were taken, the method that is used in computing the mean is important. For example, if a strong diurnal cycle exists, using data from only one release time could over or underestimate the "true" monthly mean. Moreover, as the number of observations increases, the confidence in an estimate of a mean increases since the standard deviation about the mean tends to decrease. The method of computing means used in the Monthly Climatic Data for the World, published by the National Oceanic and Atmospheric Administration (NOAA), was investigated. It was discovered that more than one method to compute an upper level monthly mean was used. Over the past 30 years, monthly means were sometimes computed by using data from only 00 GMT or 12 GMT. At other times, a combination of 00 and 12 GMT or "other times" were used in the calculation of the mean. For a particular rawinsonde station the same method of calculating means was not utilized throughout the history of the publication.

2.2.1 Simulation Study

A simulation study was conducted using July 1969 data to try to determine the sensitivity in the calculation of monthly means to variability in the number of observations and release times. This month was chosen because it had the largest or second largest number of observations for each of the 11 levels and it had the best distribution of observations over the various release times of any month.

The temperature and zonal and meridional wind components for the month of July 1969 for all 11 levels (100 to 10 mb) were plotted in histogram form. The histograms for levels 100, 50 and 10 mb represented the general features of all 11 levels. Using normal probability paper, the cumulative frequencies for the 3 variables at these 3 levels were plotted. A straight line on normal probability paper would indicate that the sample came from a population whose distribution is normal. In all 9 cases, a straight line was fitted to the data and it was found that all plotted points were within a 95 percent confidence interval using a Kolmogorov-Smirnov statistical test (Dixon and Massey, 1969). Therefore, it is safe to assume that each data sample is a realization from a normal distribution.

An overall mean for the month, $\bar{\bar{x}}$, was computed, using

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i \qquad (2\text{-}1)$$

and standard deviation, s, where

$$s = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2} \qquad (2\text{-}2)$$

and N is the total number of observations for the month at a particular pressure level. The overall mean was then compared to individual means computed from data for 00 GMT, 06 GMT, 12 GMT, 18 GMT, 00 and 12 GMT together and 06 and 18 GMT together. Using data from only one release time yielded estimates of the mean that differed from the overall mean by more than $\pm 1^{\circ}$C or ± 0.5 ms^{-1} in 32 out of 72 cases. Estimates of the mean using data from combined release times showed much better results as only 2 out of 36 estimates were greater than the $\pm 1^{\circ}$C or ± 0.5 ms^{-1} difference and both of these were less than 0.55 ms^{-1}. Means were also computed by randomly selecting 1,2,3,5,10,15,20 and 30 observations from the entire month and also by randomly selecting the same number of observations as above but only from 00 and 12 GMT data. Differences from the overall mean decreased with increasing number of observations as would be expected, and estimates of the mean using data from the 00 and 12 GMT release times displayed excellent results. In general, when data from the 00 and 12 GMT release times were used, differences of less than $\pm 1^0$C or ± 0.5 ms^{-1} were found when the number of observations was greater than or equal to 10. This result is especially important because many of the months have data from only these two release times.

2.2.2 Fourier Analysis of July 1969 Data

Finally, a Fourier Analysis using 00, 06, 12 and 18 GMT data was performed on the 50 mb July 1969 data set. Linear interpolation was used to fill in the 18 missing values out of a possible 124 values in the temperature data and 19 missing values out of a possible 124 values in the wind data. In no case were more than two consecutive values missing and most of the time the missing values occurred singly. The diurnal cycle explained about 3 percent of the variance for temperature, about 5 percent for the zonal wind component and about 12 percent for the meridional wind component. Most of the variance was explained by waves with periods greater than one day; namely, 75 percent for temperature, 82 percent for zonal wind, and 60 percent for meridional wind. Thus at 50 mb the diurnal cycle has a significant effect only on the meridional component.

2.2.3 Summary

This study indicates that waves with periods less than one day may have a significant effect on the monthly mean; namely, 22 percent for temperature, 13 percent for zonal wind and 28 percent for meridional wind variance was explained by these waves. When only two observations per day are available, the shortest wave discernable is the diurnal cycle. Hence, the effect of waves shorter than one day on the computation of the monthly mean could be significant if, for example, most of the variance were concentrated in a cycle with a period of 5 hours. However, the results of the tests where the means were computed by randomly selecting observations imply that this is not a problem where means are computed from two release times and becomes less of a problem as the number of observations increases.

2.3 Resultant Monthly Means and Variances

Figure 2a displays the monthly means and Figure 2b the monthly variances of the 50 mb zonal wind component as computed by equations 2-1 and 2-2, using all available data. The patterns in the means and variances of Figure 2 were typical of most of the other levels. At lower levels the amplitude of the pattern decreased, while at higher levels the amplitude increased. In Figure 2a, the domination of the QBO can be clearly seen. The sequence of sample monthly variances shown in Figure 2b showed that, in general, the variances from May 1952 to February 1963 were much more variable than those from September 1963 to December 1973. It should be noted that a 6-month gap at all levels existed in the data set from March to August 1963 and there were no gaps at any level from September 1963 to December 1973.

As seen in Figure 3a, before September 1963 over 21 percent of the variances were more than 35 $m^2\ s^{-2}$; whereas, as seen in Figure 3b, after September 1963, less than 5 percent of the variances were more than 35 $m^2\ s^{-2}$. The importance of a constant variance will become evident in Chapter III when the autoregressive model is discussed. Moreover, approximately 87 percent of the variance estimates before September 1963 had 45 or fewer observations, while after September 1963, 87 percent of the estimates were based on 45 or more observations. Thus the variability of the variances as shown by Figures 3a and 3b, which were the typical patterns for all the levels, are closely related to the total number of observations for the month.

Since there is such a disparity in the variance estimates before and after September 1963, because of the existence of a 6-month data gap at all levels just prior to September 1963 and because of the consistently large and nearly constant number of observations per month per level after September 1963, only the continuous data record from September 1963 to December 1973 (124 months based on over 7,200 rawinsonde observations) was used in this study. This eliminates the problems of filling in the 6-month gap in the data and the differing degrees of confidence in the estimates of the means.

2.4 Summary

Based on the above analyses, the best procedure to compute a monthly mean is to sum all the available values for a particular millibar level and variable and divide by the number of observations. There are 33 time series corresponding to 11 millibar levels for each of the 3 variables of temperature, zonal wind and meridional wind components. Each series is continuous and contains 124 elements corresponding to the months from September 1963 to December 1973. Figures 4a, 4b, and 4c summarize the monthly means and variances by level of the zonal wind component, meridional wind component and temperature time series, respectively, used in this study. Figure 4a shows a general increase in mean wind speed and variance with height for the zonal wind component. The means of the meridional wind component shown in Figure 4b generally decrease with height and are between ± 0.2 ms^{-1} above 80 mb. The variances decrease with height to 60 mb, remain constant from 60 to 30 mb and increase with height above 30 mb. In magnitude, the variances are less than 0.5 $m^2 s^{-2}$ above 80 mb except at 10 mb where the variance is about 1 $m^2 s^{-2}$. Figure 4c exhibits the well-known gradual temperature increase with height found in the tropical lower stratosphere. Except for 100 mb, the variances show a general decrease with height.

CHAPTER III

MODELING OF MONTHLY DATA

3.1 Fourier Analysis of Monthly Means

A Fourier Analysis of the monthly means from January 1964 to December 1973 in zonal wind component and temperature for Kwajalein revealed that much of the variance about the mean can be explained by the annual and semi-annual cycles and by the quasi-biennial oscillation (QBO). Since this is a 120-month period, the 10th harmonic (period of 12 months) is the annual cycle and the 20th harmonic (period of 6 months) is the semi-annual cycle. Harmonics 4, 5 and 6 (periods of 30, 24, 20 months, respectively) were grouped together to be the QBO. Figures 5a and 5b summarize the percent of variance about the mean explained by the QBO and the annual and semi-annual cycles for the zonal wind and temperature data series, respectively. The annual cycle was found to explain a minimum of 14 percent of the variance in the zonal wind at 50 mb to a maximum of 38 percent at 100 mb and a minimum of 2 percent of the variance in the temperature at 10 mb to a maximum of 82 percent at 80 mb. The semi-annual cycle explained a minimum of less than 1 percent of the variance in the zonal wind above 60 mb to a maximum of 25 percent at 80 mb and a minimum of 5 percent or less of the variance in the temperature at or below 30 mb to a maximum of 40 percent at 10 mb. The QBO was responsible for explaining a minimum of 3 percent of the variance in the zonal wind at 100 mb to a maximum of 61 percent at 50 mb and a minimum of 1 percent of the variance in the temperature at 100 mb to 38 percent at 30 and 25 mb. Thus, these 3 phenomena alone account for 65 percent of the total variance about the zonal wind component mean at 100 mb to 82 percent at 25 mb and from 62 percent of the variance about the temperature mean at 10 mb to 90 percent at 70 mb.

Figure 6 shows the monthly mean zonal wind component for 100 to 10 mb from September 1963 to December 1973. Positive values are easterly winds and negative values are westerly winds. The QBO is readily apparent in the pattern, as is its downward progression and deterioration as it approaches 100 mb. The annual and semi-annual cycles are quite evident in the lowest layers, while only the annual cycle is visible in the upper levels. Figure 7 displays the monthly mean temperature for 100 to 10 mb from September 1963 to December 1973. The annual cycle shows up very well in the lower layers, while the semi-annual cycle is very evident in the upper-most layers. The QBO is strongest in the middle layers.

As shown in Figure 4b, the monthly means of the meridional wind component for the 80 to 10 mb levels were close to zero and had a small variance. For 100 mb, the level at which the mean and variance were the largest, the mean was 1.2 ms^{-1} and the variance was 2.35 m^2s^{-2}. At this level 35 percent of the variance was explained by the annual cycle. The 100 and 80 mb levels were the only levels at which the percent of variance explained by the annual, semi-annual or QBO were greater than 10 percent.

3.2 Autoregressive Models

Because a large portion of the variance in the zonal wind and temperature is explained by these three oscillations, a method that uses previous values of a variable to predict future values for that variable would seem to be one worth investigating. Autoregressive (AR) models assign weights to the sequence of previous values and include a random component to yield the present value. The autoregressive models used in this study assume that the processes are stationary. Stationarity implies that the statistical properties of the process are independent of time, and hence the process has a constant mean and a constant variance. The monthly means and variances for all eleven levels for each of the three variables were computed and plotted. No obvious trends in the data were noted. Therefore, stationarity will be assumed.

3.2.1 Description of Univariate Model

A p^{th} order univariate AR process with zero mean is given by

$$x_t = a_1 x_{t-1} + a_2 x_{t-2} + \ldots + a_p x_{t-p} + z_t \quad (3\text{-}1)$$

where z_t is a purely random (white noise) process with zero mean and variance σ^2, and the a_i are the AR coefficients. In order to model a time series using the univariate model, AR processes from order 0 to order p are sequentially fitted to the data set, and an estimate, S_m^2 is made of σ_m^2, the residual variance for the m^{th} order process, for m = 0, 1, 2,...,p. Values of S_m^2 were computed using a computer program designed by A. J. Koscielny (School of Meteorology, University of Oklahoma) which utilizes the Burg Algorithm as formalized by Andersen (1974). The method, also known as the Maximum Entropy Method (MEM), uses recursive formulas to compute the AR coefficients such that the values of the residual variance, S_m^2, are minimized with respect to a_m, the AR coefficient for x_{t-m}.

In order to select the final order of the AR process to be fitted to the data, Akaike's Final Prediction Error Statistic (Akaike, 1971), given by

$$FPE_m = \frac{N+m+1}{N-m-1} S_m^2 \qquad (3\text{-}2)$$

where N is the total number of data points, was computed for each order m = 0, 1, ...,p. The order selected is that which minimizes (3-2). This criterion chooses the order of the AR process such that the average error for a one-step prediction is minimized with respect to the error due to the unpredictable part (z_t) of the process and the error due to the inaccuracies in estimating the AR coefficients (Jones, 1974).

Forecasts of the time series were made using subroutine FTCAST from the IMSL library (IBM 360/Model 70 computer - University of Oklahoma). This subroutine uses the AR coefficients corresponding to previous values, either newly forecasted or previously observed, up to lag p as computed from the procedure outlined above. Ninety-five percent confidence limits were also computed by subroutine FTCAST. As forecasts are continued indefinitely into the future, the variance of the forecast approaches the variance of the process (Jones, 1964b). Thus, as the confidence limits of the forecast increase, the usefulness of the forecast decreases.

3.2.2 Description of Multivariate Model

The multivariate AR (MVAR) model utilized in this study is the multivariate generalization given by Whittle (1963) of the recursive method produced by Durbin (1960) for the fitting of univariate autoregressive schemes of successively increasing order to a time series of data. It follows Jones' (1964b) procedure, but also incorporates Akaike's FPE criterion (Akaike, 1971; Goerss, 1977 and 1978) for multivariate case to select the MVAR model with the smallest mean square one-step ahead prediction error. The MVAR model of order p at time t for the k- dimensional stationary time series X_t can be written as

$$X_t = A_1X_{t-1} + A_2X_{t-2} + \ldots + A_pX_{t-p} + Z_t \qquad (3\text{-}3)$$

where X_t and Z_t are column vectors of dimension k and the A's are the k x k MVAR coefficient matrices.

In order to model the k time series, M + 1 MVAR processes whose order m increases from 0 to M are successively fitted to the k dimensional data series, X_t. Utilizing Akaike's FPE criterion (Akaike, 1971), given by

$$FPE_m = \left(\frac{N + mk + 1}{N - mk - 1}\right)^k \left|S_{m,k}\right| \tag{3-4}$$

limits the selection of M to be less than (N - 1)/ k so that the denominator in (3-4) is greater than zero. $\left|S_{m,k}\right|$ is the determinant of the residual covariance matrix for order m and the k time series. After computing an FPE for each of the M + 1 processes, the MVAR model that minimizes (3-4) is selected as the model for the k time series to be predicted. Calculation of the residual covariance matrix, the FPE's and the MVAR coefficients were performed using a computer program designed by J.S. Goerss (School of Meteorology, University of Oklahoma).

Forecasts of the k time series were made using a computer program designed by A.J. Koscielny which multiplied the MVAR coefficient matrices for a particular lag time by the column vectors of the data series corresponding to the particular lag and summed the result with the other similar products up to the order (lag) selected by Akaike's FPE criterion. Forecast values then become lagged values for forecasts beyond that time. Ninety-five percent confidence limits were computed utilizing a computer program designed by C.E. Duchon (School of Meteorology, University of Oklahoma) which was based on theoretical developments by

Jones (1964b) and Box and Jenkins (1970).

CHAPTER IV

ANALYSIS OF FORECASTS OF MONTHLY MEANS USING AR MODELS

The univariate and multivatiate AR models discussed in Chapter III were used to make numerous sets of forecasts of 12 successive monthly means of zonal wind, meridional wind, and temperature based on 100 to 112 monthly means from the September 1963 to December 1972 data set. The 12 forecasts were calculated, using

$$
\begin{aligned}
X^*_{t+1} &= a_1X_t + a_2X_{t-1} +\dots+ a_pX_{t-p+1} \\
X^*_{t+2} &= a_1X^*_{t+1} + a_2X_t +\dots+ a_pX_{t-p+2} \qquad (4\text{-}1) \\
X^*_{t+12} &= a_1X^*_{t+11} + a_2X^*_{t+10} +\dots+ a_pX_{t-p+12}
\end{aligned}
$$

where p is the order of the AR process and the a_i's are the AR coefficients. In the multivariate autoregressive (MVAR) model X_t is a column vector of dimension k and the a_i's are k x k coefficient matrices. Twelve monthly means based on the individual soundings from the same 112-month period as above were also computed to obtain climatological means for January through December for the zonal wind, meridional wind and temperature. These climatological means provided 12 climatological "forecasts" for each of the three variables.

Seventeen sets of forecasts of the zonal wind were made using the MVAR model (see Table 1). The various cases differ as to which millibar levels were forecast, the number of months used to make the forecasts and whether or not alignment was used and, if so, how much. By alignment is meant shifting the data so that if Figure 6 (zonal wind means) were replotted after the aligning process was completed, the slant in the contours would become vertical. This technique was tried since the QBO is responsible for explaining a large portion of the variance from about 70 to 10 mb and the low order MVAR models that were usually chosen would, of course, only use the last few monthly means at each pressure level. Recalling that one of the characteristics of the QBO was its downward progression of about 1 km per month (Reed, 1965), a switch to a new wind regime first noticed at 10 mb would not be noted at 100 mb until about 14 months later. Hence, low order models seemingly would lose some valuable information. Therefore, aligning the data enables low order models to utilize the information that low order models of non-aligned data do not use. In this study, the one kilometer per month value seemed to fit the data for the 1968 to 1971 period and the one and one-half kilometer per month value seemed to fit the 1972 to 1973 period. Hence, both alignments were tried.

Nine variables were chosen for some of the cases because the upper 9 levels, 70-10 mb, are totally in the stratosphere. The climatological standard atmosphere for Kwajalein by month indicated that the tropopause over Kwajalein varied from 94 mb in January to 112 mb in August (Range Reference Atmosphere Committee, 1974). Further, a visual inspection of the 11 time series revealed that the upper 9 levels were very similar in their general pattern, with the magnitude of the means generally increasing with height. The two lower levels, 100 and 80 mb, were combined since they were similar in appearance but differed from the upper 9 levels. One reason for the difference is that the amplitude of the QBO diminished rapidly near 80 and 100 mb. Forecasts using only the 3 upper levels were performed to determine if there was a relationship between the accuracy of forecasts and the number of levels for which forecasts were made.

Four sets of forecasts of the meridional wind and temperature were made using the MVAR model (see Table 2 and 3, respectively). The four cases used for both variables differ only in the levels forecasted. Case 3 used all 11 levels. Case 4 used the lower 2 and case 5 the upper 9 levels. These latter two cases were chosen for consistency with the cases for the zonal wind forecasts and because the upper 9 levels are totally in the stratosphere, while the lower 2 are sometimes in the troposphere. Case 6 utilized the upper 3 levels and, as in the case for the zonal wind forecasts, was chosen to determine if there was a relationship between the accuracy of the forecasts and the number of levels for which forecasts were made. No alignment of the meridional wind or temperature data was appropriate.

In order to get a quantitative measure of the effectiveness of the AR forecasts, four types of RMSEs (root-mean-square-errors) were calculated and compared with RMSEs computed for the climatology "forecasts". First, a RMSE was computed for each of the 12 forecasted time steps using

$$\mathrm{RMSE}(j) = \left[\sum_{i=1}^{N_L} (0_i - F_i)^2 / N_L\right]^{1/2} \qquad (4\text{-}2)$$

where RMSE(j), $j=1,2,\ldots,N_F$, is the RMSE for the j^{th} time step. 0_i and F_i are the observed and forecasted monthly mean values, respectively, at the i^{th} pressure level, and N_L is the number of pressure levels used in the model. Second, the average of the N_F RMSEs from (4-2) was computed. Third, a RMSE was calculated for each pressure level utilized using

$$\mathrm{RMSE}(i) = \left[\sum_{j=1}^{N_F} (0_j - F_j)^2 / N_F\right]^{1/2} \qquad (4\text{-}3)$$

where RMSE(i), $i=1,\ldots,N_L$, is the RMSE for the i^{th} pressure level, 0_j and F_j are the observed and forecasted mean values, respectively, for the j^{th} time step at that level, and N_F is the number of forecasts made for a pressure level. Fourth, the average of the N_L RMSEs from (4-3) was computed. The results of the forecasts of the zonal wind will be presented first, followed by the results for the meridional wind and then those for temperature.

4.1 Monthly Mean Zonal Wind Forecasts

Table 1 contains a summary of the various cases used including forecast method, which of the 11 levels from 100 to 10 mb were forecast, number of months used in the forecast, whether alignment was used and if so, how much and AR order selected. The ordering of the 19 cases is as follows: climatology (1), univariate (2), multivariate: non-aligned using 11 variables (3, 4), aligned using 11 variables (5,6), non-aligned using 2 variables (7), non-aligned using 9 variables (8, 9, 12), aligned using 9 variables (10, 11, 13), non- aligned using 3 variables (14, 15, 18), and aligned using 3 variables (16, 17, 19).

The four RMSE values discussed above were computed for each of the 19 cases. The results are summarized in Table 4a which gives the RMSEs for the zonal wind forecast by pressure level using equation 4-3 and Table 4b which gives the RMSEs for the zonal wind forecasts by forecast time step using equation 4-2.

The comparison of the univariate model with climatology using RMSEs shows that the univariate model was superior to climatology. The average RMSEs for all 11 levels and for the forecast time steps was reduced by about one-third. Moreover, the 6 univariate RMSEs corresponding to the first 6 months forecasted were up to 57 percent less than the corresponding climatology RMSEs. The univariate RMSEs for the pressure levels were up to 67 percent smaller than the climatology RMSEs for 9 out of 11 levels. Figure 8 displays the univariate and climatology forecasts for 20 mb, the pressure level at which the univariate RMSEs showed the most improvement (67 percent) over the climatology RMSEs.

The remaining cases utilized the multivariate model and can be divided into aligned and non-aligned. The non-aligned cases will be discussed first. All 11 levels were employed in case 3 to make forecasts of all 11 levels. This case displayed the lowest average RMSEs when forecasting all 11 levels (Table 4a and 4b), being over 40 percent less than the climatological RMSEs. In addition, the RMSEs for the first 6 forecast time steps of case 3 were up to 72 percent smaller than climatology, while the RMSEs for 9 out of the 11 pressure levels of case 3 were up to 58 percent less than that for climatology. Figure 9 displays the climatology and multivariate forecasts for case 3 for 15 mb. This pressure level showed one of the largest percentage decreases in RMSEs with respect to climatology.

Cases 7 and 8, where only 2 and 9 levels were used and forecasted, respectively, also did a better job than climatology. When taken together as the method for forecasting all 11 levels, the average RMSE for the 11 levels was about 35 percent less than that for climatology.

To test to see if using fewer than 9 or 11 levels from 70 to 10 mb range would improve the forecasts, the upper 3 levels (case 14) were chosen. The RMSE values for the 3 levels were less than climatology's, but were not as small as those for case 3. One reason may be that in case 3 more information was used in making the forecasts than in case 14, i.e., the sample aize was 11 x 112 = 1232 while in case 14, the sample size was 3 x 112 = 336.

The remaining cases dealt with one of the two a-ligning processes. From Table 4a and 4b it is apparent that by comparing case 5 with 6, 10 with 11 and 16 with 17 an alignment of 1 km month^{-1} generally gave better results than 1-1/2 km month^{-1}. A comparison of cases 11 with 13 and 17 with 19 disclosed the sensitivity of the RMSE values to the number of data points used (see Table 1) and hence which particular months are being forecast. The paradoxical deterioration in the skill of the forecasts by using more months was caused by the fact that the rapid transition to large negative values occurred from months 101 to 104 of the upper level time series. This may indicate a weakness in the multivariate autoregressive procedure used in this study when the data record is "short". Here "short" means that there is only enough data to cover a few cycles of the longest period of interest (i.e., the QBO). This weak-ness has been discussed by Ulrich and Bishop (1975) and Jones (1976).

Because a direct comparison between cases 3 and 5 or 8 and 10, et cetera, cannot be made since the sample size in 5 and 10 were smaller than in 3 and 8, cases 4, 9, 12, 15, and 18 were done to give further insight as to the skill of the alignment process and the sensitivity to sample size. From Table 4a, in most of the cases, the a-lignment process seemed to yield better one-year forecasts than when no alignment was done. However, it should be noted that in most of the latter series of non-aligned cases (4, 9, 12, 15, 18) more of the overall RMSE value can be attributed to forecast months 7 through 12 than in the aligned cases, e.g., using Table 4b compare case 9 with cases 10 and 11. Also, the RMSE values have been shown to be sensitive to which months were forecasted and the months in cases 4, 9, 12, 15 and 18 were different then the months in the aligned cases. From these comparisons no definite conclusions can be drawn regarding the effect of the alignment process on the forecasts made.

Nevertheless, the non-aligned data (cases 2, 3, 7, 8, 14) did make significantly better forecasts than climatology. The study suggests that forecasts of the monthly mean zonal wind using AR models out to at least 6 months and maybe to 12 months, which were better than climatology, may be credible. From Table 4b, RMSEs for cases 2, 3 and 7 and 8 combined were all smaller than climatology for each time step out to 6 months. The picture becomes somewhat unclear for the 7 to 12 months forecast time steps. Climatology tended to have smaller RMSEs for time steps 7 through 9 and the AR forecasts tended to have smaller RMSEs for time steps 10 through 12. Thus, the effect of the months forecasted rather than a characteristic of the model may be confusing the analysis effort. More forecasts using other data sets may help shed some light on the question.

4.2 Monthly Mean Meridional Wind Forecasts

The same four RMSEs used in 4.1 were calculated for a meridional wind climatology "forecast" and 5 other cases. Table 2 contains a summary of the various cases used including forecast method, which of the 11 levels from 100 to 10 mb were forecast, number of months used in the forecast, and AR order selected. No alignment of the meridional wind data was made.

The results are summarized in Table 5a which gives the RMSEs for the meridional wind forecast by pressure level and Table 5b which gives the RMSEs for the meridional wind forecasts by forecast time step. Because the magnitudes of the meridional wind were small and the variances were also small (see Figure 4b), there was very little difference between the RMSEs for the various methods. Hence, either monthly climatological values or an AR process of order zero, i.e. the mean value of the series, can be used with good results for apparently as long a period of time as one desires.

4.3 Monthly Mean Temperature Forecasts

The same four RMSEs that were calculated in 4.1 and 4.2 were also computed for the monthly mean temperature climatology "forecast" and the same 5 other cases used in 4.2. Table 3 summarizes the 6 cases by listing the forecast method, the levels used in the forecast, the number of months used in the forecasts and the AR order selected. No alignment of the temperature data was made.

The results have been tabulated in Table 6a which gives the RMSEs for the mean monthly temperature forecasts by pressure level and Table 6b which gives the RMSEs for the mean monthly temperature forecasts by forecast time step. The two average RMSEs for the climatology forecasts were less than the other cases. However, the difference between the average RMSEs is only about 0.6°C or less among the cases involving all 11 levels. The univariate model did better than climatology for 4 of the 11 levels, while the multivariate models tended to do better at the higher levels where the annual cycle was less dominant, and the series less deterministic. The univariate and multivariate models (cases 1, 2 and 3) also did better than climatology for 3 out of the first 6 forecast time steps, while climatology was consistently better (up to 1.38°C) than the models for time steps 7 through 12. Nevertheless, the differences between the RMSEs for climatology and the AR and MVAR models involving all 11 levels (i.e. cases 1, 2, 3, and 4 and 5 combined) were usually less than 0.5°C.

Although the differences are small, it is still difficult to beat the climatology temperature forecasts. This may be due to some extent to the fact that the temperature variances are relatively small (Figure 4c). Most of them are one to two orders of magnitude smaller than the zonal wind variances (Figure 4a) in numerical value (ignoring units). An example of one of the forecasts made from case 2 is provided by Figure 10 and one of the forecasts from case 5 is shown in Figure 11.

CHAPTER V

SUMMARY AND CONCLUSIONS

Monthly means of 100 to 10 mb zonal and meridional wind components and temperature were compiled for Kwajalein for the period September 1963 to December 1973. Univariate autoregressive (AR) and multivariate autoregressive (MVAR) models were used to forecast monthly means of the three variables for a 12-month period using 100 to 112 months from the data set through 1972. In order to get a quantitative measure of the effectiveness of the AR forecasts, two sets and two average root-mean-square-errors (RMSE) (see Chapter 4) were calculated and compared with RMSEs computed for the climatology "forecasts". The climatology forecasts were based on climatological monthly means computed from the September 1963 to December 1972 data set.

For zonal wind forecasts, average RMSEs from MVAR models for 12 forecast time steps were up to 44 percent less than the climatology RMSE. Additionally, the RMSEs for the first 6 forecast time steps of the MVAR model using all 11 levels were up to 72 percent less than the climatology RMSE. The RMSEs for the pressure levels using all 12 forecast time steps were up to 58 percent smaller than climatology in 9 out of the 11 levels for this same MVAR case. A technique called alignment was used in which the zonal wind data set was shifted so that the slant in the easterly and westerly wind contours would become vertical. Results of the comparisons made between the forecasts from the aligned and non-aligned data series were inconclusive. Analyses of the univariate AR and MVAR models suggested that forecasts better than climatology could be made by both the AR and MVAR models for periods of 6 to 12 months.

An analysis of the meridional wind component revealed that climatological values or the mean value of the series could be used with good results for apparently as long a period of time as one desired.

For temperature forecasts, climatology tended to have smaller RMSEs than either the univariate or multivariate models, but the differences were usually about 0.5°C or less among the cases involving all 11 levels. However, the univariate did better than climatology for 4 of the 11 levels. The MVAR models tended to perform better at higher levels where the annual cycle was less dominant, and thus less deterministic. Although the differences between the RMSEs for climatology and the AR and MVAR models involving all 11 levels were small, it was still difficult to beat the climatology temperature forecasts. One reason for this may be that the temperature variances were relatively small (Figure 4c), especially when they are compared in order of magnitude (ignoring units) to the zonal wind variances (Figure 4a).

This study suggests that AR methods can be used to make tropical stratospheric forecasts of 6 to 12 months that are about as good as and in some cases, i.e., zonal wind forecasts, better than climatological (as defined in this thesis) forecasts. Additional research is needed to substantiate this claim.

One technique that may improve the AR forecasts would be to remove the annual and semi-annual components and fit an AR model to the residuals. Then, one would use the AR model to generate forecasts and add back in the annual and semi-annual components. This technique and the technique used in this study should be tried on other locations with longer records (perhaps Balboa).

A multivariate model involving temperature and the zonal wind component could be tried also. The multivariate extension of the Burg estimation procedure which is "better" than the Yule-Walker equations for "short" data records, where "short" means that one only has enough data to cover a few cycles of the longest period of interest (i.e., the QBO) (Ulrich and Bishop, 1975), should be tested (Jones, 1976). From these additional studies it is hoped that not only will the forecasts be improved, but that credible predictions for more forecast periods into the future will be able to be made.

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Table 1. Summary of Cases for Zonal Wind Forecasts

CASE	METHOD	LEVELS FORECAST (NUMBER)	NUMBER MONTHS USED	ALIGNMENT	AR ORDER SELECTED
1	Climatology	100-10 (11)	112	No	-
2	Univariate	100-10 (11)	112	No	*
3	MVAR	100-10 (11)	112	No	2
4	MVAR	100-10 (11)	102	No	1
5	MVAR	100-10 (11)	102	1 km mo^{-1}	3
6	MVAR	100-10 (11)	102	1½ km mo^{-1}	2
7	MVAR	100-80 (2)	112	No	2
8	MVAR	70-10 (9)	112	No	2
9	MVAR	70-10 (9)	100	No	2
10	MVAR	70-10 (9)	100	1 km mo^{-1}	3
11	MVAR	70-10 (9)	100	1½ km mo^{-1}	2
12	MVAR	70-10 (9)	104	No	2
13	MVAR	70-10 (9)	104	1½ km mo^{-1}	2
14	MVAR	20-10 (3)	112	No	3
15	MVAR	20-10 (3)	100	No	2
16	MVAR	20-10 (3)	100	1 km mo^{-1}	4
17	MVAR	20-10 (3)	100	1½ km mo^{-1}	2
18	MVAR	20-10 (3)	104	No	2
19	MVAR	20-10 (3)	104	1½ km mo^{-1}	2

* (Level - order) 100-12, 80-22, 70-13, 60-13, 50-3, 40-2, 30-28, 25-28, 20-25, 15-25, 10-25.

Table 2. Summary of Cases for Meridional Wind Forecasts

CASE	METHOD	LEVELS FORECAST (NUMBER)	NUMBER MONTHS USED	AR ORDER SELECTED
1	Climatology	100-10 (11)	112	-
2	Univariate	100-10 (11)	112	*
3	MVAR	100-10 (11)	112	0
4	MVAR	100-80 (2)	112	6
5	MVAR	70-10 (9)	112	0
6	MVAR	20-10 (3)	112	0

* (Level - order) 100-6, 80-1, 70-1, 60-14, 50-0, 40-1, 30-3, 25-0, 20-0, 15-1, 10-1.

Table 3. Summary of Cases for Temperature Forecasts

CASE	METHOD	LEVELS FORECAST (NUMBER)	NUMBER MONTHS USED	AR ORDER SELECTED
1	Climatology	100-10 (11)	112	-
2	Univariate	100-10 (11)	112	*
3	MVAR	100-10 (11)	112	2
4	MVAR	100-80 (2)	112	4
5	MVAR	70-10 (9)	112	2
6	MVAR	20-10 (3)	112	5

* (Level - order) 100-11, 80-13, 70-14, 60-17, 50-15, 40-15, 30-22, 25-22, 20-23, 15-15, 10-13.

Table 4a. Zonal Wind Forecast RMSE By Pressure Level ($m\ s^{-1}$)

CASE \ LEVEL (mb)	100	80	70	60	50	40	30	25	20	15	10	AVERAGE	CASE
1	4.30	3.09	5.03	7.08	7.67	6.83	6.95	11.04	13.47	16.16	17.33	9.18	1
2	5.40	2.95	3.19	3.39	5.63	7.54	6.68	5.40	4.47	10.25	11.35	6.02	2
3	5.79	3.41	2.78	3.00	3.99	5.13	5.79	5.73	6.47	7.66	9.35	5.37	3
4	5.48	5.21	6.84	10.54	13.38	13.60	13.39	14.27	16.44	20.09	22.73	12.91	4
5	5.31	4.05	4.92	7.47	9.02	9.09	9.31	8.73	7.14	7.63	8.05	7.34	5
6	5.25	3.54	4.40	6.05	7.46	8.35	10.90	11.35	12.46	14.90	16.61	9.21	6
7	6.34	3.38										4.86*	7
8			2.60	2.94	4.36	5.92	6.76	6.67	7.41	8.62	10.20	6.16*	8
9			6.36	9.13	11.26	11.18	7.99	6.76	8.51	13.10	17.38	10.19	9
10			3.48	3.81	3.52	4.57	7.51	8.46	9.90	12.88	15.55	7.74	10
11			3.91	5.60	6.74	7.61	9.85	10.26	10.86	13.04	16.45	9.37	11
12			4.92	7.54	9.51	10.67	12.71	13.54	14.92	17.23	18.40	12.16	12
13			2.96	3.48	6.01	9.91	13.03	12.99	13.51	15.12	16.86	10.43	13
14									7.32	8.20	9.32	8.28	14
15									8.90	12.73	17.19	12.94	15
16									15.56	16.94	16.83	16.44	16
17									14.30	15.50	17.79	15.86	17
18									16.27	19.02	20.77	18.69	18
19									14.88	17.97	19.99	17.61	19

* Average RMSE for cases 7 and 8 combined is 5.93 ms^{-1}.

Table 4b. Zonal Wind Forecast RMSE By Forecast Time Step ($m\ s^{-1}$)

CASE \ TIME STEP	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE	CASE
1	13.58	13.92	13.80	12.22	10.79	8.64	5.63	5.41	6.21	7.87	8.40	10.35	9.78	1
2	5.87	6.40	6.58	7.50	6.29	5.46	6.50	6.67	6.82	8.23	5.88	6.24	6.54	2
3	3.86	4.09	4.74	5.38	6.08	5.97	7.85	7.81	7.14	6.32	2.69	3.82	5.48	3
4	2.26	3.97	7.01	10.32	12.12	12.59	10.69	11.67	16.31	22.88	19.67	20.97	12.54	4
5	3.57	4.69	6.39	7.34	8.30	8.43	7.63	7.34	6.53	8.16	8.61	10.86	7.32	5
6	2.80	4.83	6.70	8.23	8.31	6.85	3.57	10.42	15.43	17.38	13.49	11.00	9.08	6
7	2.33	1.52	4.96	7.14	9.55	5.41	2.95	2.35	1.39	8.65	0.94	3.68	4.24	7
8	4.43	4.93	5.30	5.64	5.88	7.23	9.84	9.84	8.91	5.93	3.08	3.91	6.24	8
9	1.25	4.14	5.69	5.26	4.42	7.45	10.44	12.10	10.49	10.83	15.46	22.35	9.16	9
10	2.80	4.48	6.18	6.93	8.39	9.71	10.75	9.77	8.72	9.63	10.03	12.87	8.36	10
11	2.29	4.82	6.59	7.08	8.15	9.78	10.58	9.17	4.44	10.53	16.34	18.35	9.01	11
12	3.68	5.94	7.37	8.38	7.25	8.78	14.02	20.59	16.68	18.24	17.37	12.18	11.71	12
13	2.15	4.62	6.11	7.18	10.30	16.54	19.88	19.62	13.56	9.50	4.59	4.02	9.84	13
14	7.14	6.56	4.70	9.52	10.36	11.90	12.80	10.71	7.45	2.08	3.96	4.55	7.64	14
15	1.77	3.77	4.36	1.69	1.89	6.65	9.86	12.28	8.42	9.69	21.43	34.46	9.69	15
16	2.54	2.77	3.37	3.23	4.76	6.53	6.23	7.82	18.87	26.48	29.31	33.63	12.13	16
17	1.47	1.96	3.95	5.98	8.56	12.60	14.38	12.48	3.07	17.97	29.35	34.64	12.20	17
18	2.14	7.03	10.75	13.58	9.72	9.68	20.78	34.00	25.76	26.48	23.87	12.91	16.39	18
19	2.83	8.35	12.62	12.90	4.02	15.18	26.25	31.84	25.92	22.51	14.63	5.51	15.21	19

Table 5a. Meridional Wind Forecast RMSE By Pressure Level ($m\ s^{-1}$)

CASE \ LEVEL (mb)	100	80	70	60	50	40	30	25	20	15	10	AVERAGE	CASE
1	1.31	0.66	0.57	0.52	0.55	0.42	0.54	0.28	0.55	0.72	1.50	0.69	1
2	1.71	0.90	0.59	0.55	0.51	0.41	0.52	0.25	0.49	0.61	1.61	0.74	2
3	1.75	0.89	0.59	0.50	0.51	0.41	0.50	0.25	0.49	0.62	1.53	0.73	3
4	1.84	0.88										1.36*	4
5			0.59	0.50	0.51	0.41	0.50	0.25	0.49	0.62	1.53	0.60*	5
6									0.49	0.62	1.53	0.88	6

* Average RMSE for cases 4 and 5 combined is 0.74 ms^{-1}.

Table 5b. Meridional Wind Forecast RMSE By Forecast Time Step ($m\ s^{-1}$)

CASE \ TIME STEP	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE	CASE
1	0.56	0.52	1.32	0.57	1.10	0.69	0.75	0.53	0.63	0.46	0.94	0.77	0.74	1
2	0.82	0.63	1.35	0.26	1.06	0.50	0.99	0.86	0.77	0.37	1.07	1.08	0.81	2
3	0.57	0.59	1.36	0.30	1.07	0.49	1.02	0.86	0.78	0.36	1.08	1.10	0.80	3
4	0.61	0.68	0.76	0.47	2.05	0.08	1.69	1.79	1.64	0.29	2.31	2.24	1.22	4
5	0.58	0.50	1.46	0.27	0.90	0.53	0.80	0.49	0.47	0.39	0.48	0.58	0.62	5
6	0.89	0.48	2.43	0.13	1.53	0.73	0.81	0.64	0.48	0.49	0.39	0.58	0.80	6

Table 6a. Temperature Forecast RMSE By Pressure Level (°C)

CASE \ LEVEL (mb)	100	80	70	60	50	40	30	25	20	15	10	AVERAGE	CASE
1	0.72	1.67	1.90	1.66	1.36	1.15	1.23	1.41	1.69	1.70	1.76	1.48	1
2	1.79	2.33	1.63	0.91	1.12	1.41	1.85	1.86	2.18	2.08	1.54	1.70	2
3	1.94	3.75	3.21	2.23	1.66	1.32	1.41	1.55	1.82	1.69	1.71	2.03	3
4	1.51	3.17										2.34*	4
5			3.09	2.17	1.64	1.31	1.34	1.47	1.78	1.74	1.79	1.81*	5
6									1.66	1.54	1.46	1.55	6

* Average RMSE for cases 4 and 5 combined is 1.91°C.

Table 6b. Temperature Forecast RMSE By Forecast Time Step (°C)

CASE \ TIME STEP	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE	CASE
1	1.48	2.63	2.08	1.18	1.01	1.29	1.12	1.32	2.15	1.24	0.69	0.52	1.39	1
2	1.49	2.71	1.99	1.11	0.74	1.60	1.64	1.99	2.46	2.09	1.10	0.83	1.65	2
3	1.44	3.41	3.15	2.06	0.92	1.26	2.30	2.70	2.43	1.56	1.02	1.87	2.01	3
4	1.27	2.52	4.59	3.30	1.86	0.54	1.51	2.72	2.85	3.14	1.16	1.13	2.22	4
5	1.49	3.39	2.48	1.95	1.12	1.02	1.79	2.19	2.13	1.20	0.84	1.41	1.75	5
6	1.23	1.79	1.15	0.83	0.74	1.10	1.26	2.47	3.12	1.39	0.73	0.72	1.38	6

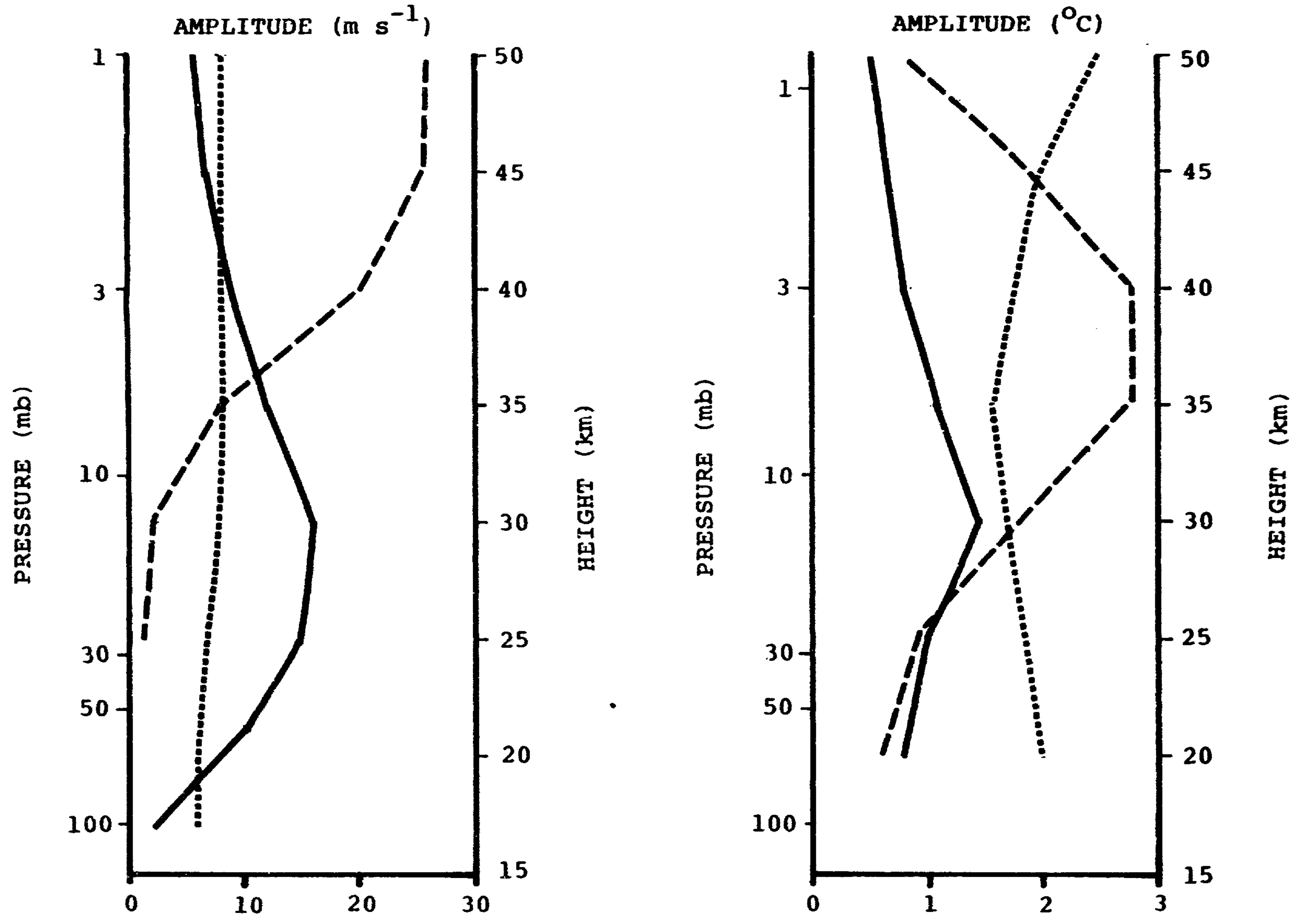


Figure 1. Approximate amplitude of annual (····), semi-annual (----), and QBO (——) cycles for zonal wind and temperature in the tropical stratosphere over 9^{O}N latitude.

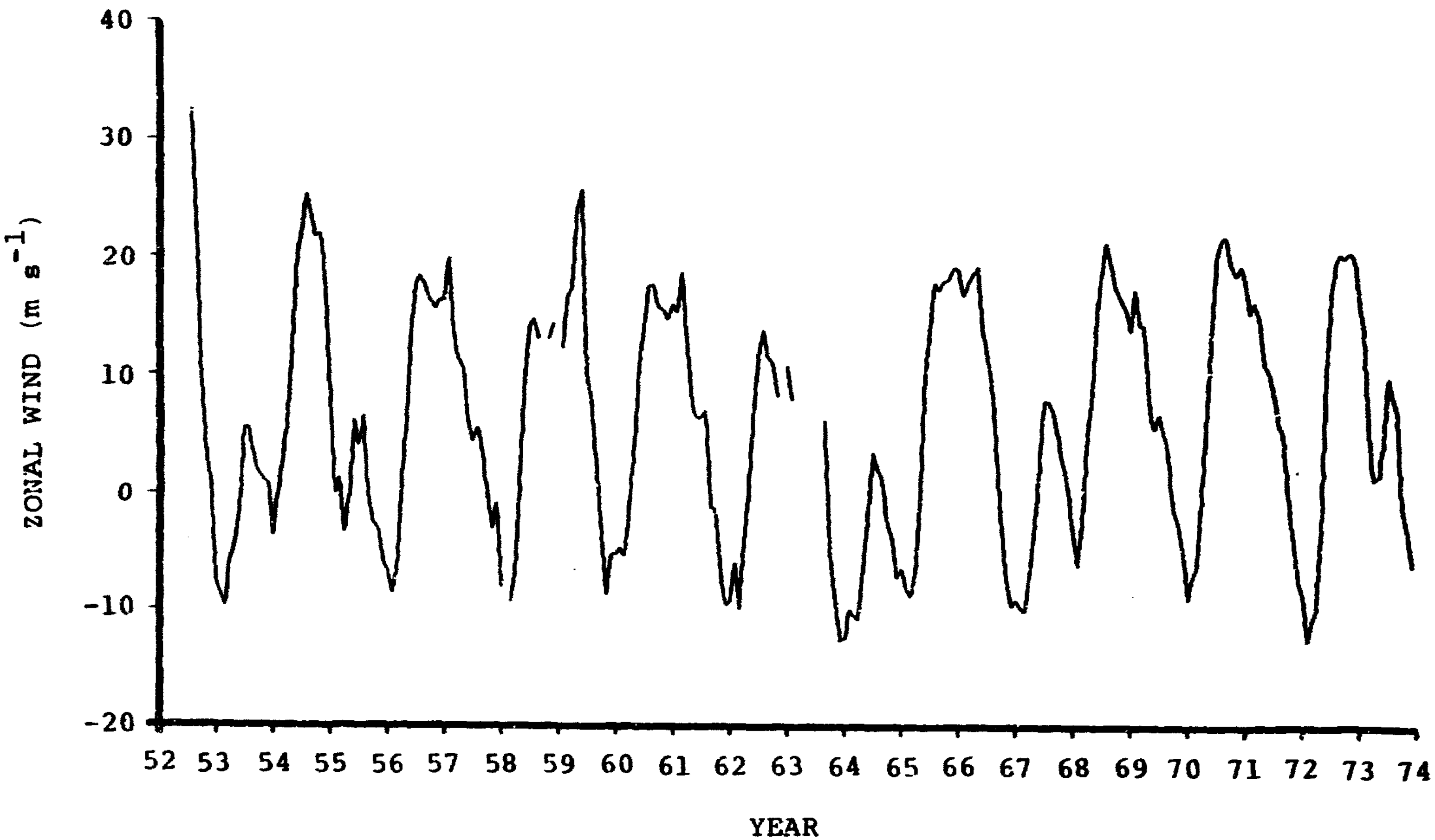


Figure 2a. 50 mb monthly means of zonal wind component (u)

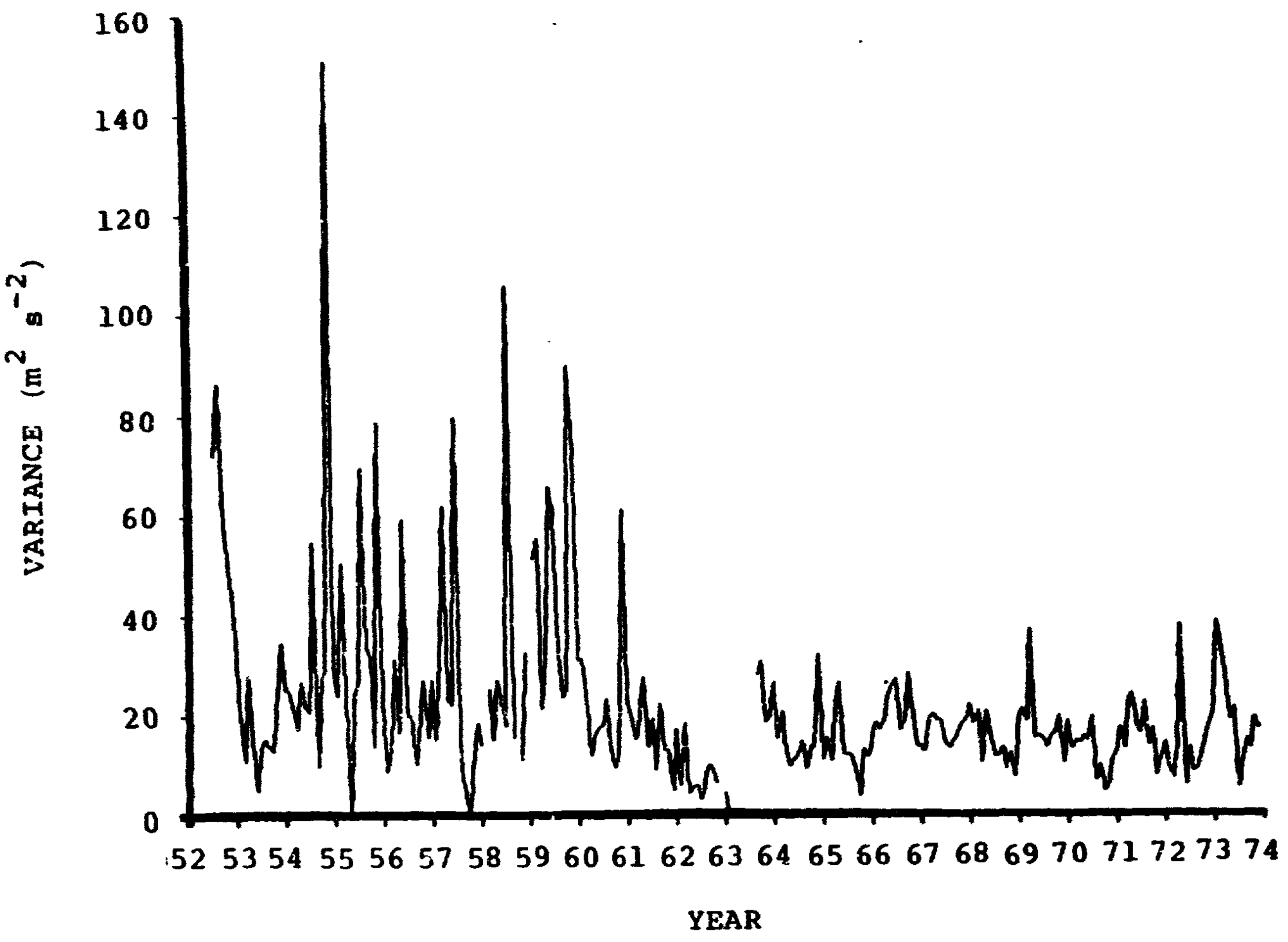


Figure 2b. 50 mb monthly variances of zonal wind component (u)

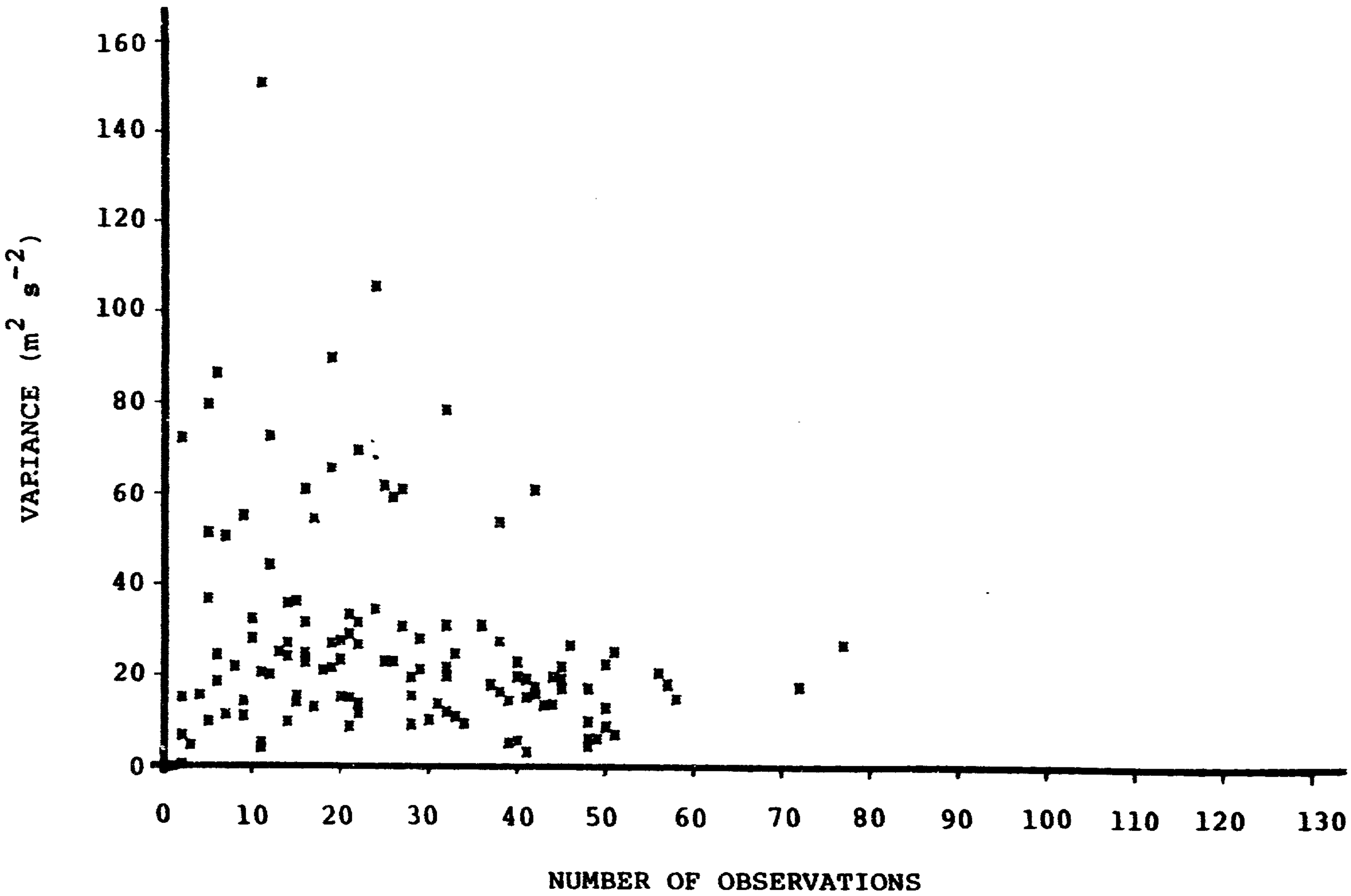


Figure 3a. 50 mb zonal wind monthly variances vs. number of observations for a month for the period May 1952 to February 1963.

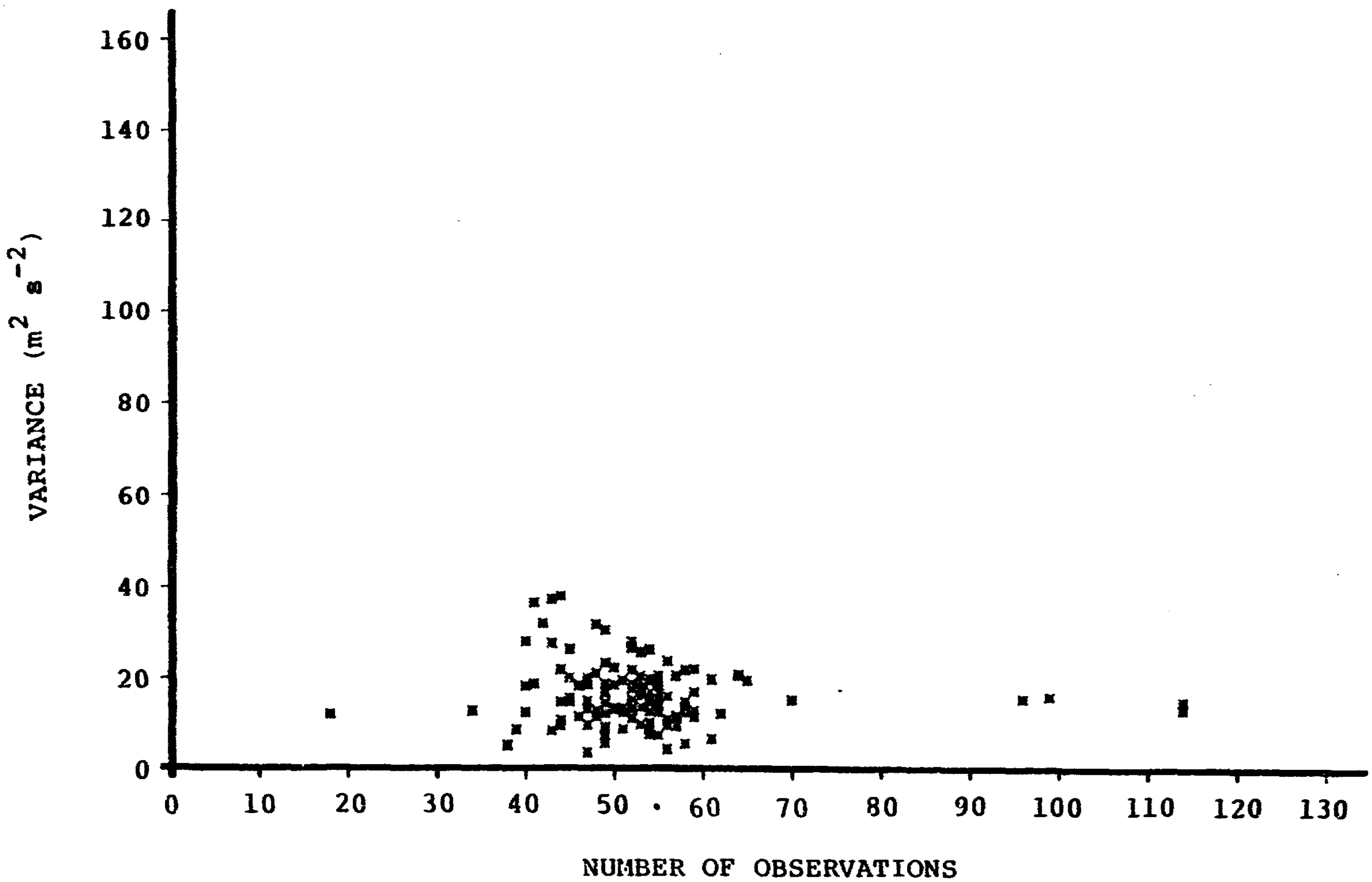


Figure 3b. 50 mb zonal wind monthly variances vs. number of observations for a month for the period September 1963 to December 1973.

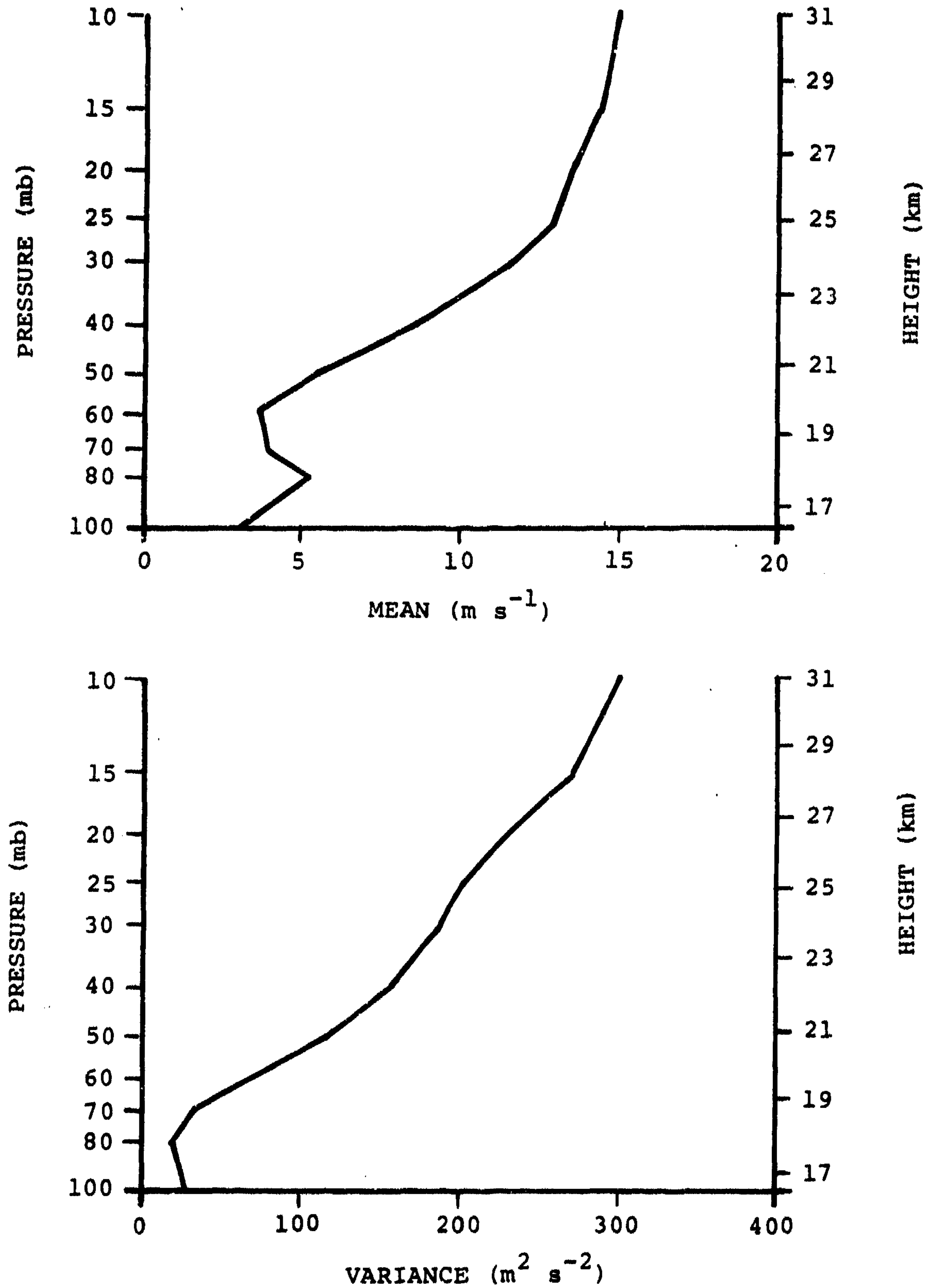


Figure 4a. Mean and variance of zonal wind data series (September 1963 to December 1972)

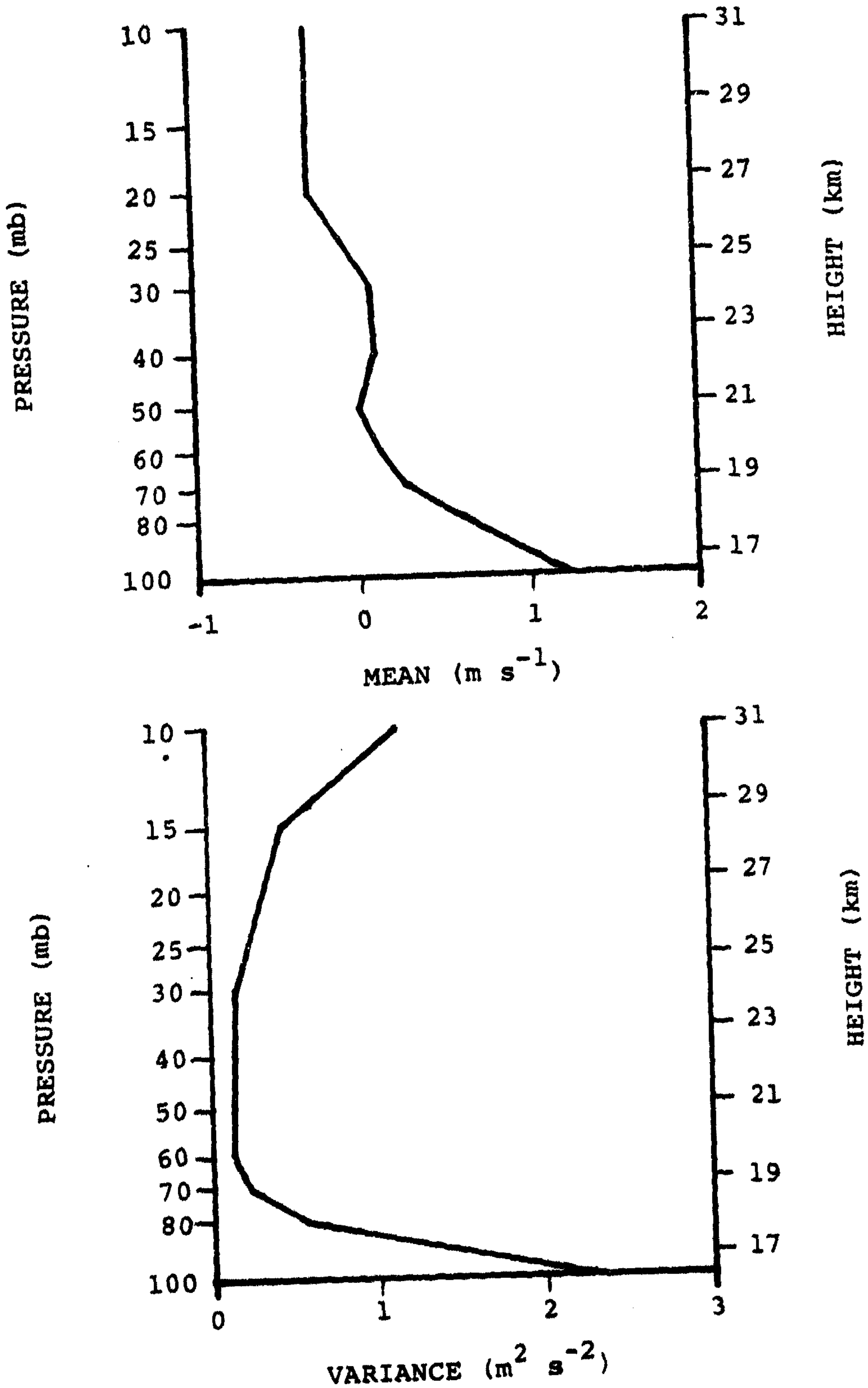
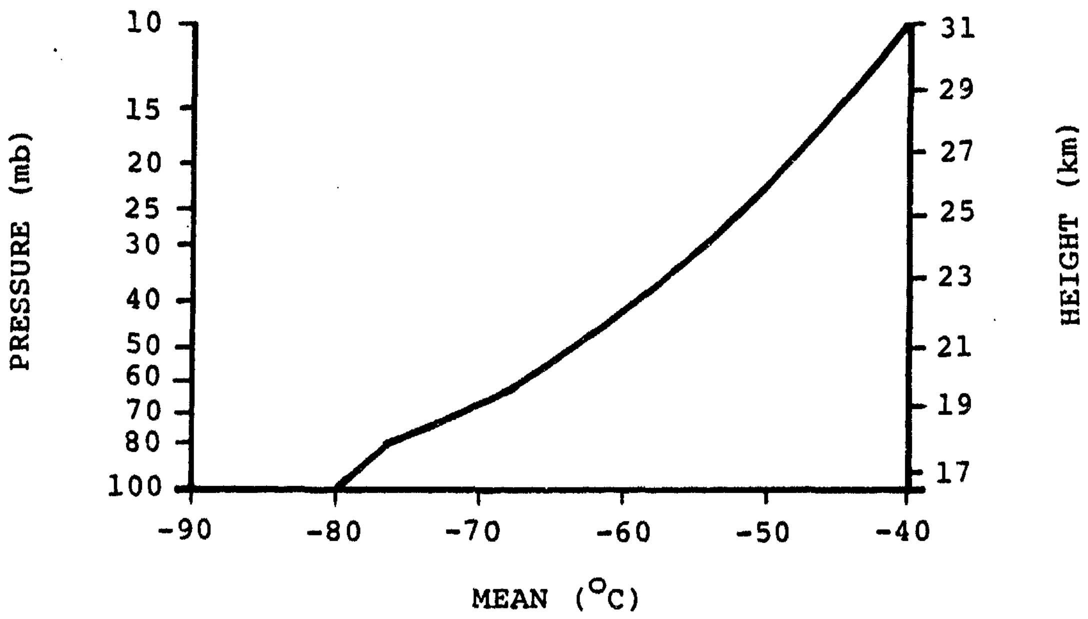


Figure 4b. Mean and variance of meridional wind data series (September 1963 to December 1972)



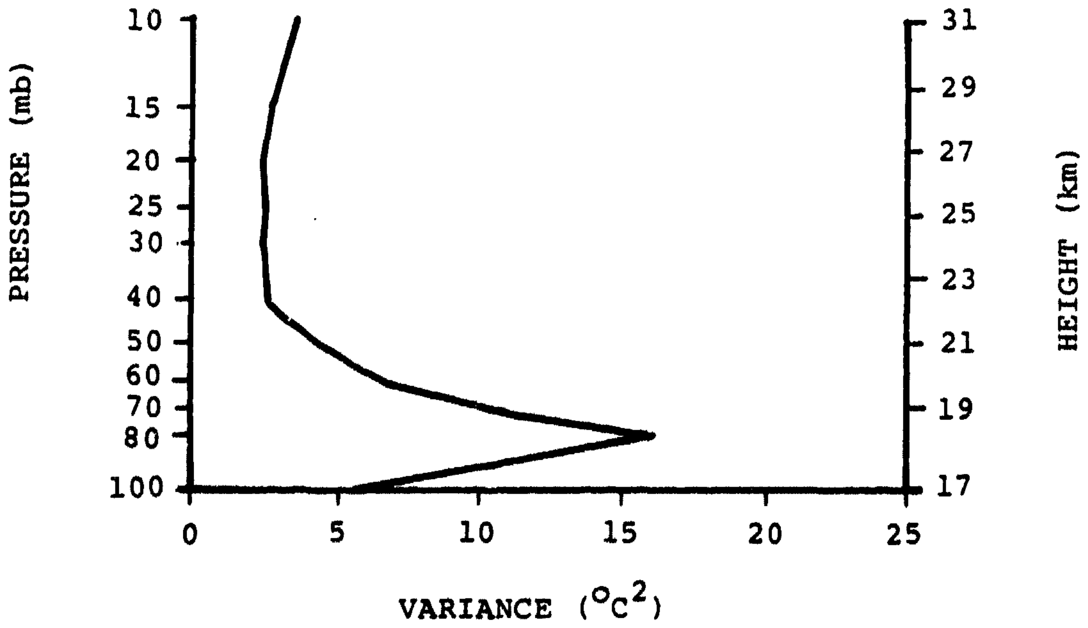


Figure 4c. Mean and variance of temperature data series (September 1963 to December 1972)

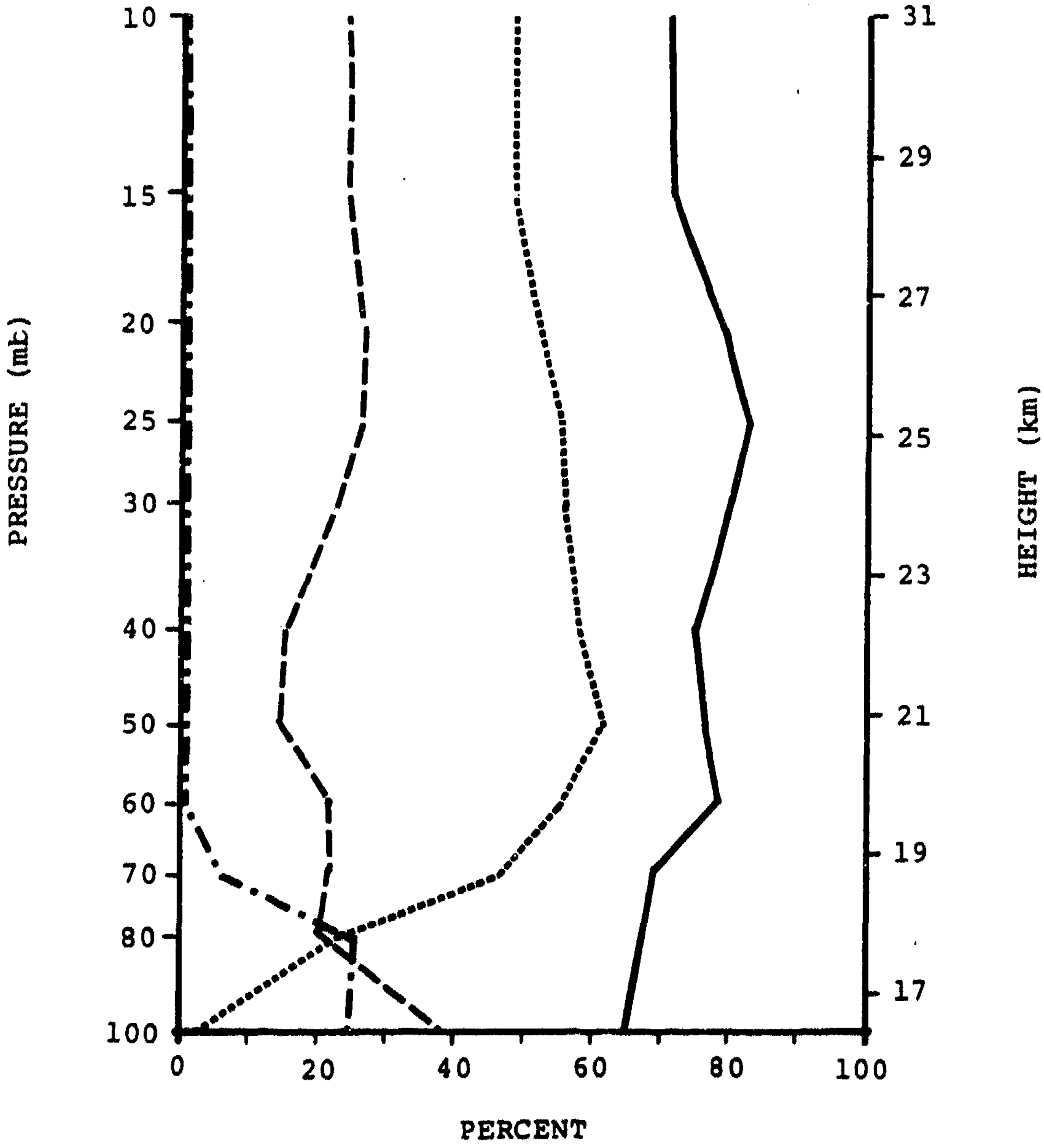


Figure 5a. Fourier Analysis of monthly mean zonal wind showing percent of variance explained by QBO (····), annual (----) and semi-annual (-·-·) cycles and their sum (——).

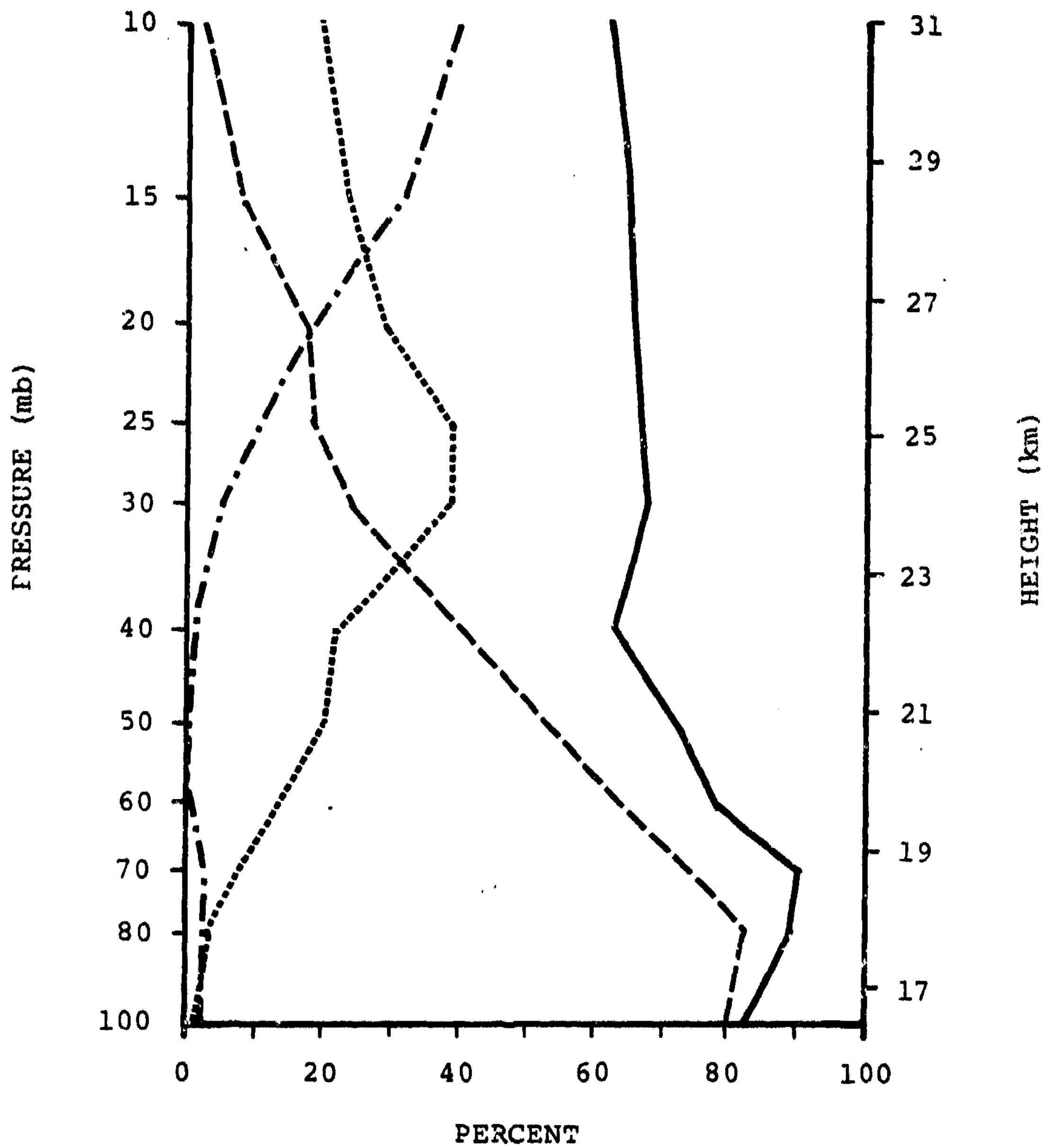


Figure 5b. Fourier Analysis of monthly mean temperature showing percent of variance explained by QBO (····), annual (----) and semi-annual (-·-·) cycles and their sum (——).

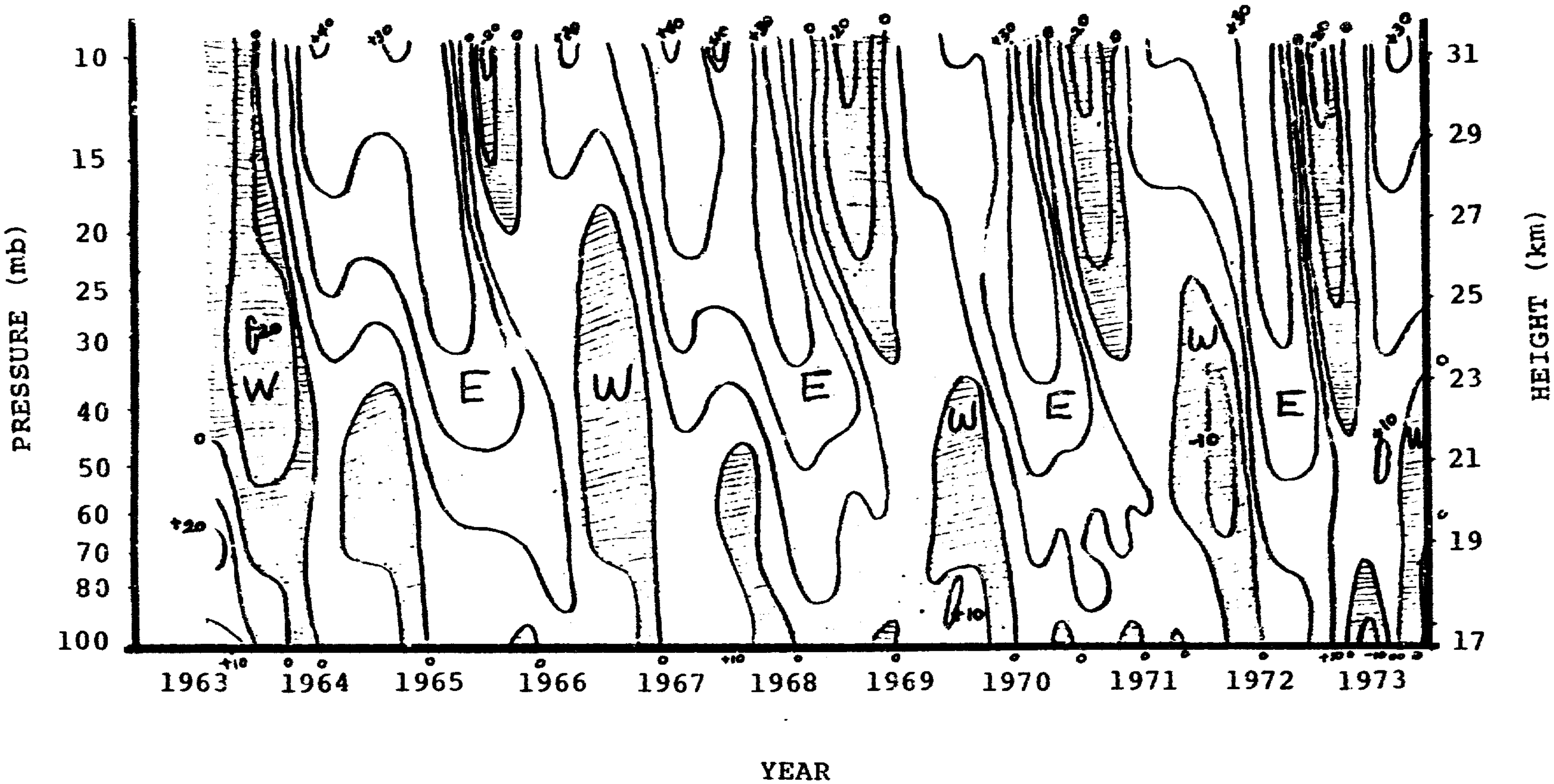


Figure 6. Monthly mean zonal wind components for 100 to 10 mb from 1963 to 1973 (+ East, - West (shaded)).

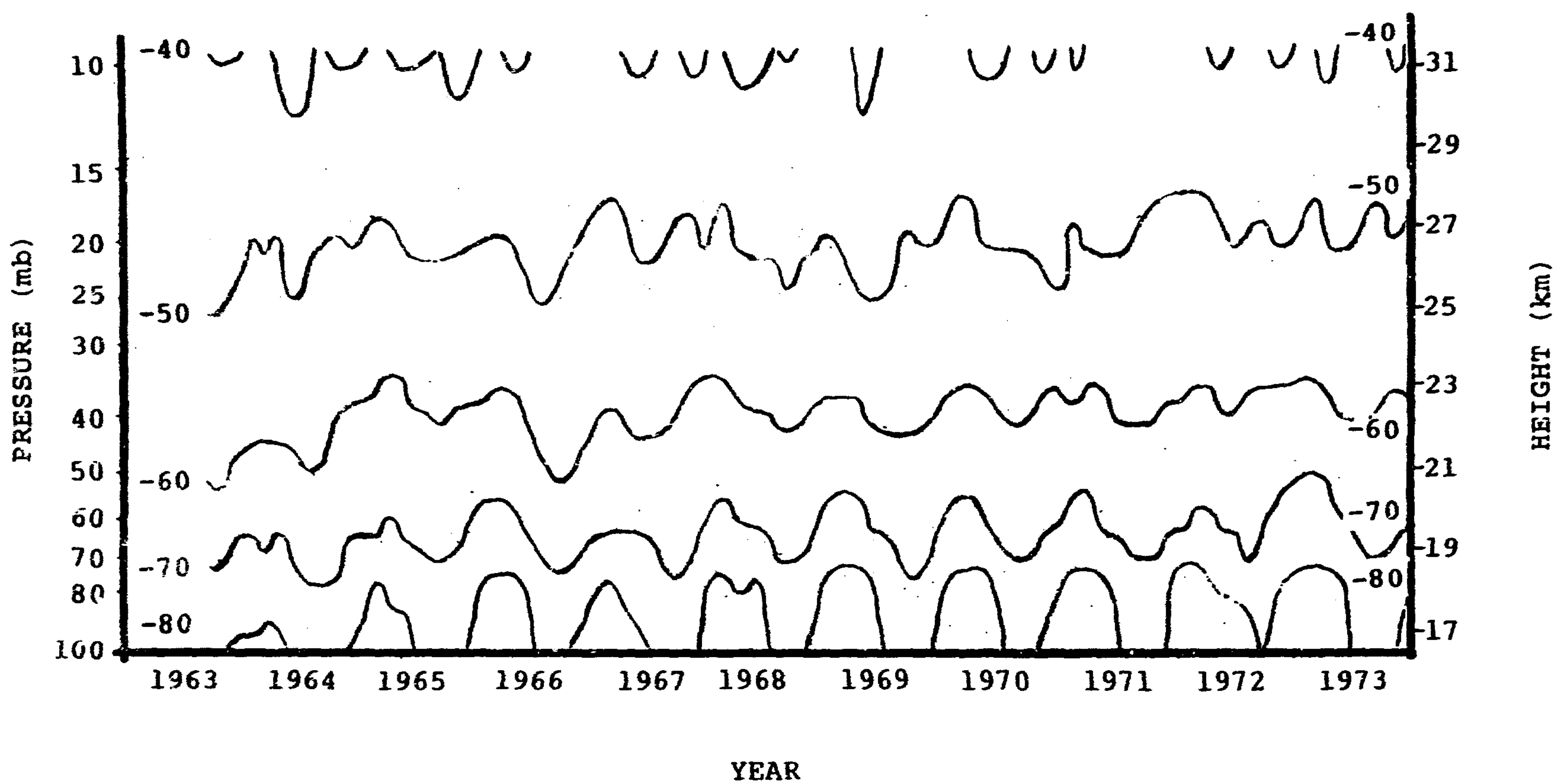


Figure 7. Monthly mean temperature for 100 to 10 mb from 1963 to 1973.

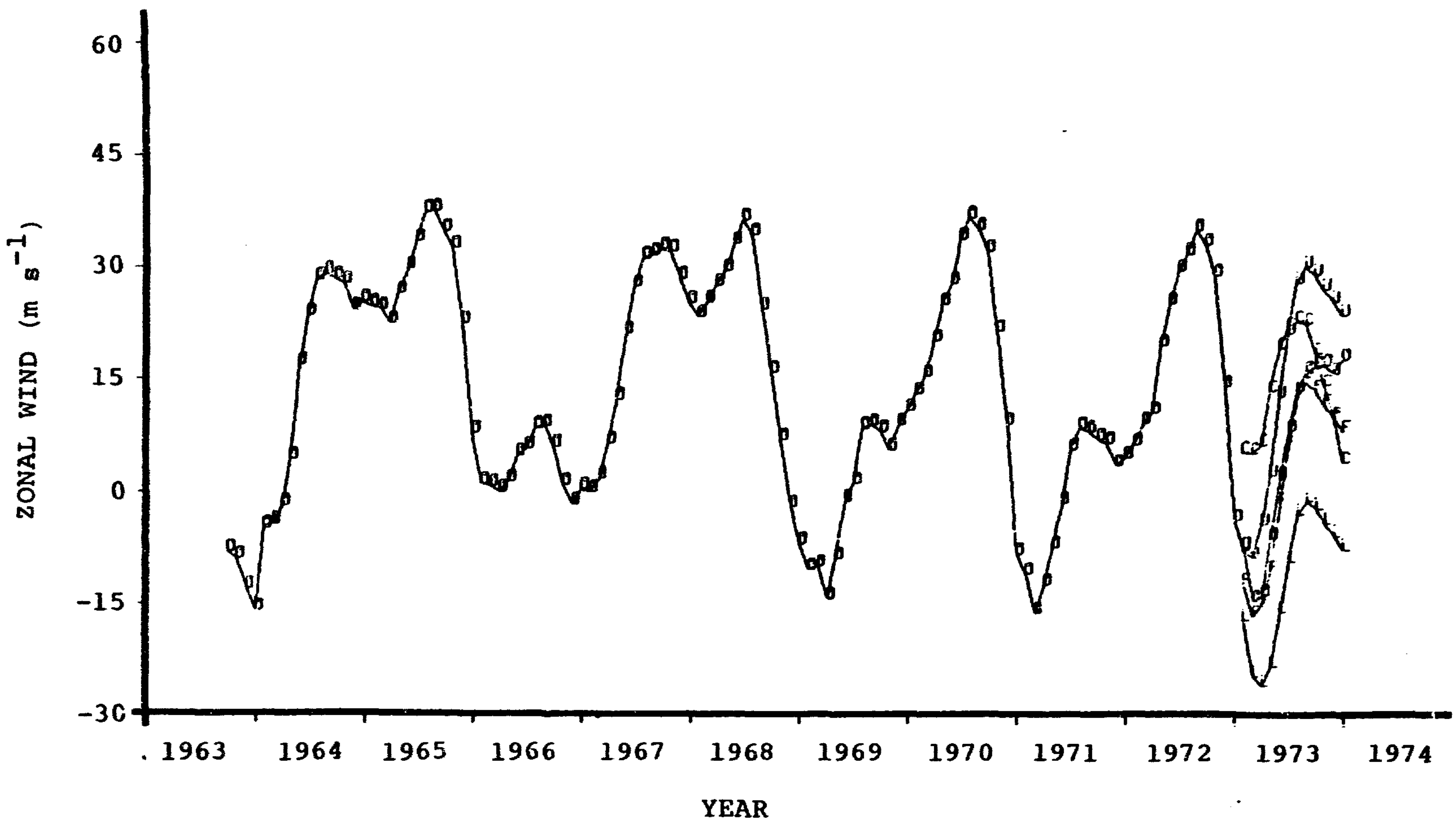


Figure 8. 20 mb zonal wind component observations (O), univariate forecasts (F), climatology (C), and upper (U) and lower (L) 95% confidence limits.

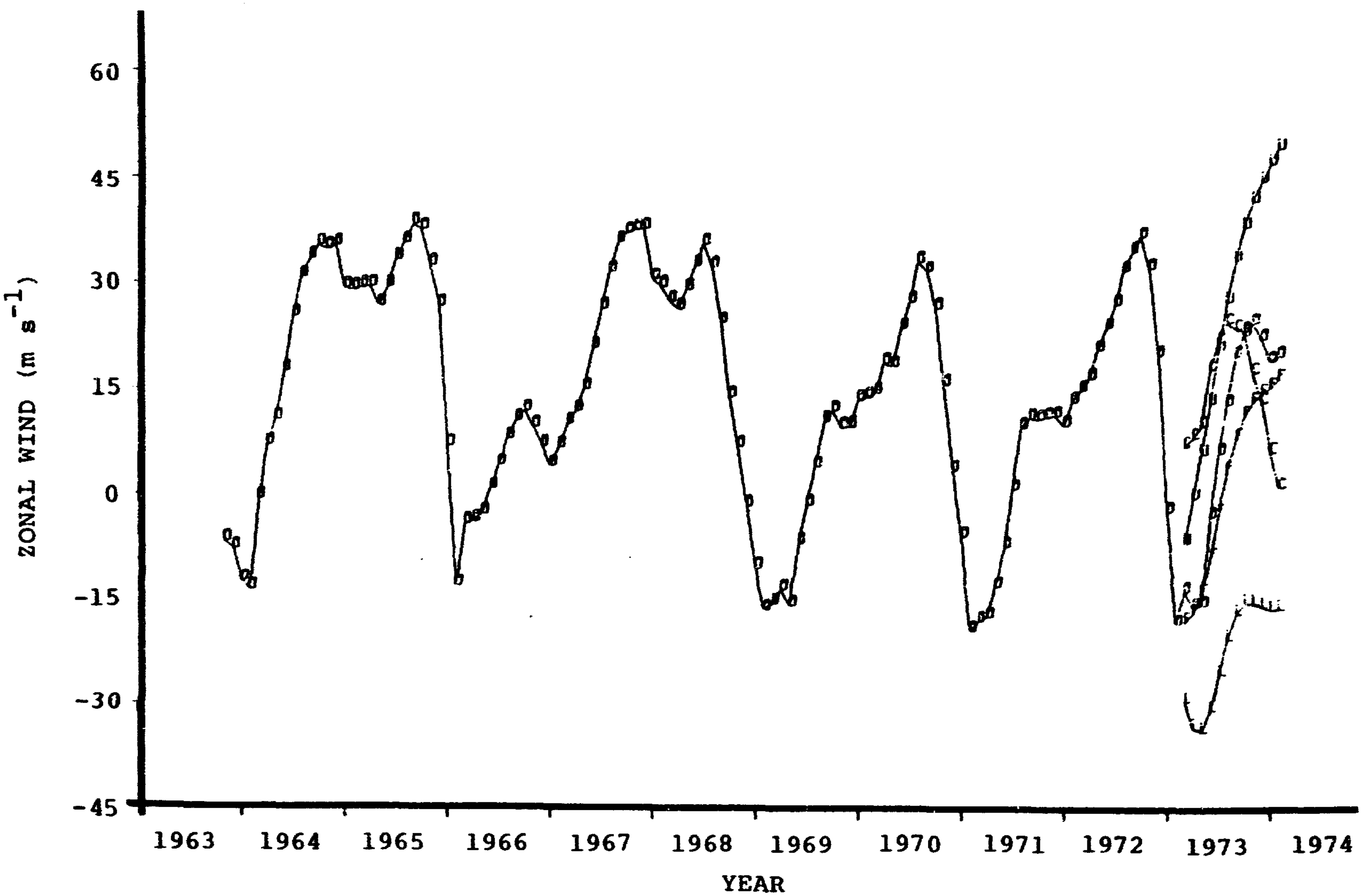


Figure 9. 15 mb zonal wind component observations (O), multivariate forecasts (F), climatology (C), and upper (U) and lower (L) 95% confidence limits.

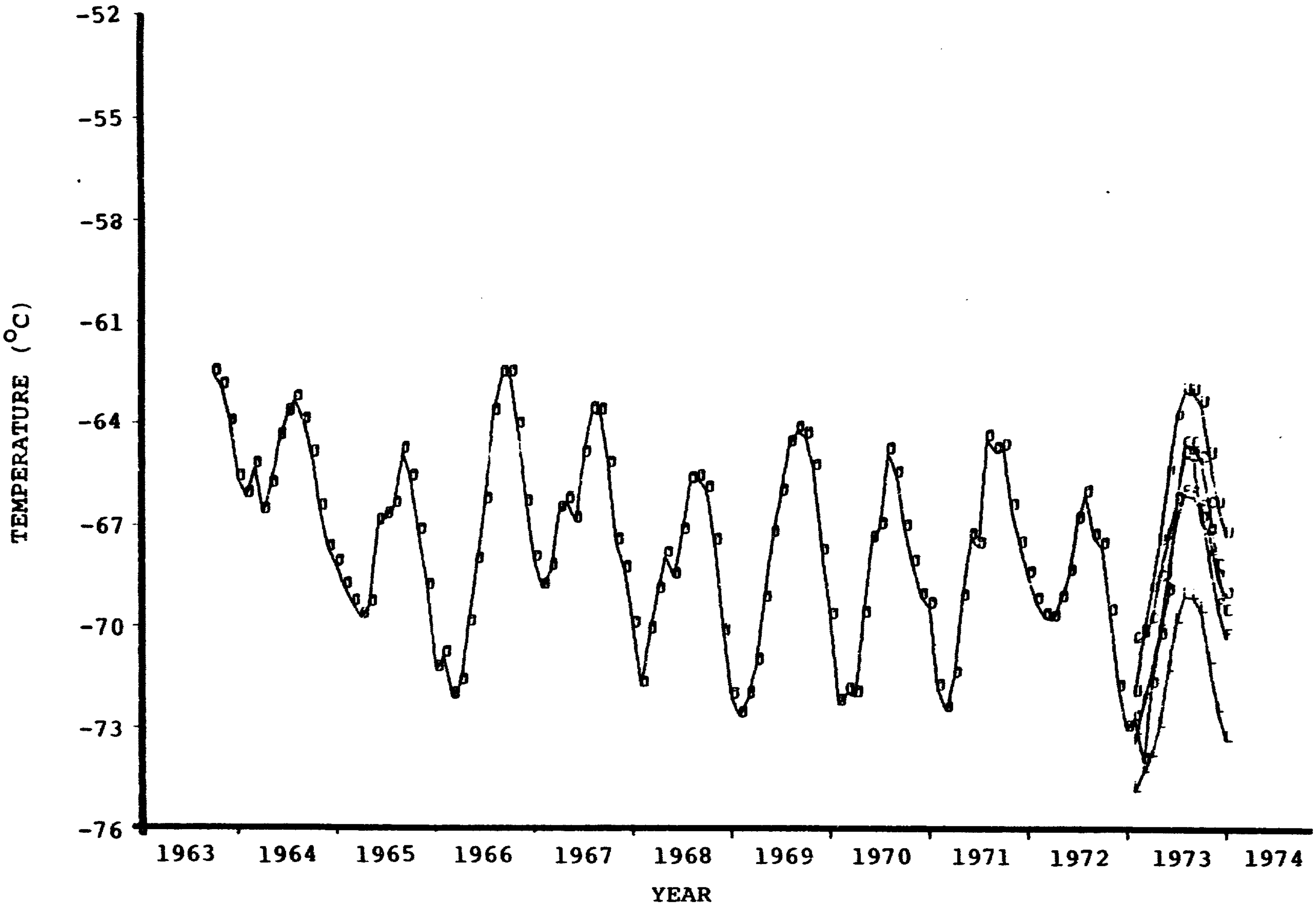


Figure 10. 60 mb temperature observations (O), univariate forecasts (F), climatology (C), and upper (U) and lower (L) 95% confidence limits.

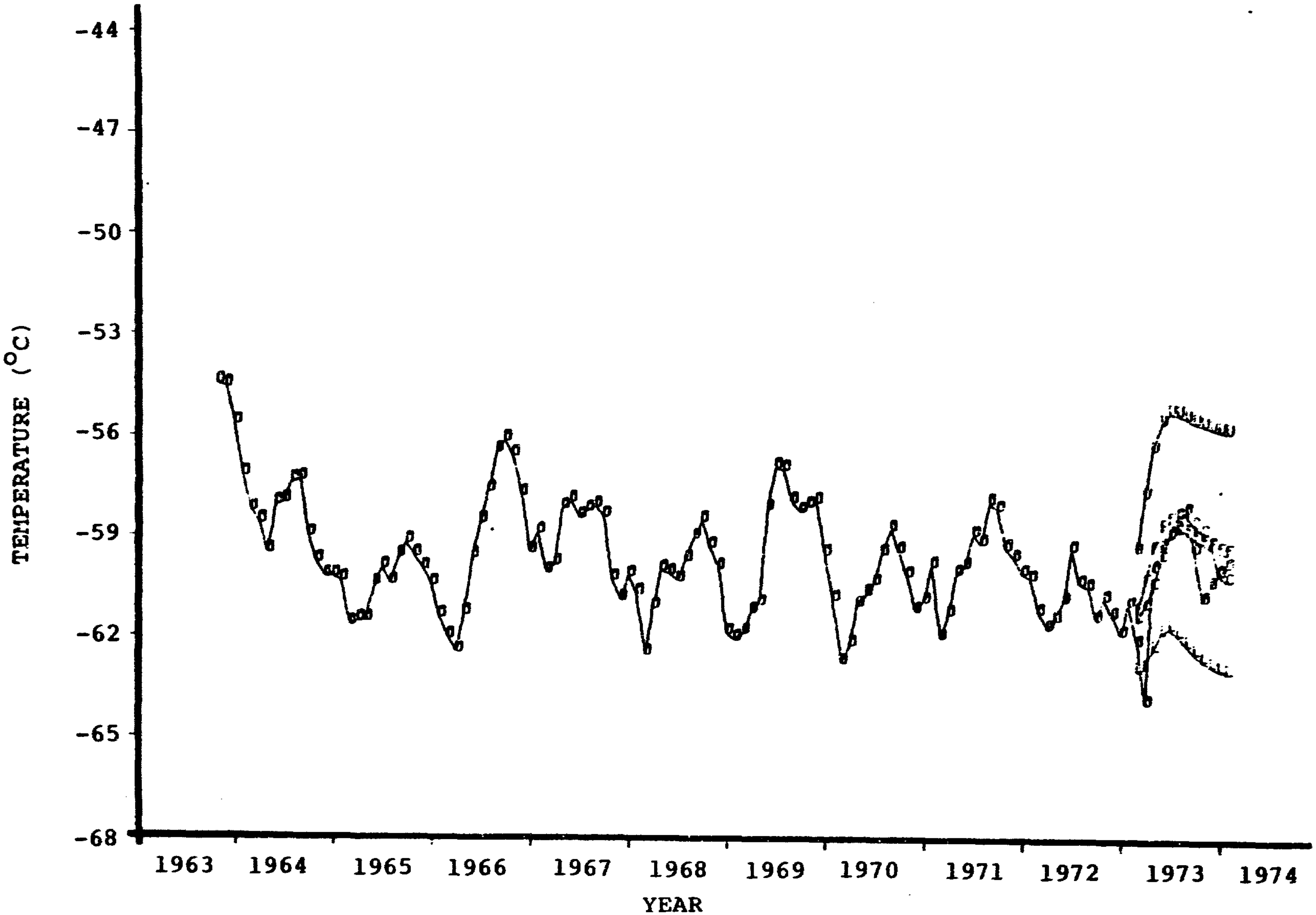


Figure 11. 40 mb temperature observations (O), multivariate forecasts (F), climatology (C), and upper (U) and lower (L) 95% confidence limits.